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Review of latent thermal-energy storage systems for solar air-conditioning systems

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Abstract

Solar air-conditioning is an important approach to satisfy the high demand for cooling given the global energy situation. The application of phase-change materials (PCMs) in a thermal storage system is a way to address temporary power problems of solar air-conditioning systems. This paper reviews the selection, strengthening, and application of PCMs and containers in latent thermal storage system for solar air-conditioning systems. The optimization of PCM container geometry is summarized and analyzed. The hybrid enhancement methods for PCMs and containers, and the cost assessment of latent thermal storage system are discussed. The more effective heat transfer enhancement using PCMs was found to mainly involve micro-nano additives. Combinations of fins and nanoadditives, nanoparticles and metal foam are the main hybrid strengthening method. However, the thermal storage effect of hybrid strengthening is not necessarily better than single strengthening. At the same time, the latent thermal storage unit has less application in the field of solar air-conditioning systems, especially regarding heat recovery, because of its cost and thermal storage time. The integration of latent thermal storage units and solar air-conditioning components, economic analysis of improvement technology, and quantitative studies on hybrid improvement are potential research directions in the future.

Keywords: Solar air-conditioning; Phase-change material; Hybrid enhancement; Latent thermal storage.

1. Introduction

The global energy situation is an important problem, and a global solution is needed to solve this problem. The combination of a highly stressed environment with a shortage of fossil fuel and climate change suggests a rapid transition towards a more sustainable energy infrastructure. Several countries, including the United States [1], Indonesia [2], and China [3] encourage the use of renewable energy and energy conservation methods. Financial subsidies are [4-7] offered to encourage both corporations and end-users to choose renewable energy options. Figure 1 shows that the installed renewable energy capacity in China [8] has increased, mainly owing to new public policies. The installed solar energy capacity grew fastest from 2009 to 2016. In 2016, the installed solar-power capacity was 76.31 million kW, ~81% higher than the previous year. Solar energy has a great long-term potential among renewable energy resources.

Place Figure 1 here

For the cooling applications, the development of solar energy as a renewable energy has recently received unprecedented attention [9-11]. Solar cooling has great potential because of the high global need, environmental and energy saving benefits, and typically high availability of sunlight when cooling is needed. In essence, solar air-conditioning systems (SACSs) use solar energy instead of conventional energy to supply heat for a conventional cooling cycle. The key technology of SACS is not solar energy but the air-conditioning system itself. Air-conditioning systems capable of utilizing low-grade heat energy such as absorption, adsorption, and ejection systems have been known before the 1930s [12]. However, these cooling systems were of limited practical use because of their high cost and low efficiency when electricity-driven steam compression refrigeration systems became available [13]. After the 1970s, the energy crisis facilitated the development of SACS, especially the absorption refrigeration technology [14]. Current techniques that use solar energy for cooling are illustrated in Figure 2. SACSs are typically based on photoelectric conversion or photothermal conversion. Air-conditioning, refrigeration and other cooling demands can be performed using different SACS types, such as adsorption, absorption, and ejection. Today, solar absorption cooling technology has reached the stage of large-scale industrial production. It is the best-developed form of SACS, followed by adsorption cooling [15]. Asia became the largest market for thermally driven chillers, thanks to the installation of large-scale solar-energy-driven cooling systems in India and China [16]. Solar thermal-cooling systems are already used by thousands of residential and commercial users.

Place Figure 2 here

Although solar air-conditioning has become an established industry, the

intermittent nature of solar energy still restricts its performance and reliability [17]. The energy-storage system, perhaps the most important component in a SACS, helps mitigate the temporal or local differences between solar energy supply and demand. Therefore, theoretical and experimental studies on energy storage have a great impact on the development of SACSs. Energy storage for SACS has two purposes: (1) Heat storage - storing the excess heat absorbed from solar collectors and recovered heat losses from other systems. (2) Cold storage - accumulate the extra cooling capacity stored by chillers (cold storage use). Most energy storage systems usually use water as the storage medium, i.e., these devices are large and heavy, making them unsuitable for many applications. Phase-change materials (PCMs) can help break through the current limitations of SACS, because of their high storage capacity and an almost constant operating temperature. Therefore, PCMs are widely used in solar energy storage system, especially in the shell of solar buildings [18-20], solar water collector [21, 22], and HVAC systems [23].

Studies on latent thermal-energy storage mainly focus on the mining and preparation of PCMs with excellent storage and improved heat transfer properties [24-26]. Some comprehensive reviews are available on the application of PCMs for heating, ventilation, and air-conditioning systems. Abduljalil et al. [27] reviewed the use of PCMs in air-conditioning systems. The article systematically summarized the applicable PCM in air conditioning system. The influence of the internal structure of PCM container on the heat storage efficiency was summarized. The influence of the geometric parameters of the PCM container was neglected. Li et al. [28] summarized the available cold storage materials for air conditioning and focused on the use of phase-change slurry. Zhai et al. [29] discussed PCMs for cold storage in air-conditioning systems, especially composite PCMs. Pintaldi et al. [30] reviewed appropriate PCMs and design schemes for use in SACSs. The paper focused on LTESSs in the high temperature ($>100\text{ }^{\circ}\text{C}$) cooling systems. Khan et al. [31] reported latent thermal storage methods for solar absorption air-conditioning systems and concentrated mainly on the PCMs used in single-effect absorption air-conditioning systems. Omara and Abelnour [32] introduced different methods for integrating PCMs into air-conditioning systems. In addition, the application of PCMs in improving energy saving of air-conditioning systems is discussed. The review focuses more on the effect and improvement of the PCM side on the latent thermal storage performance of air-conditioning systems and less on the PCM container side. However, the abovementioned studies are neither systematic nor sufficiently comprehensive, and include overlaps. These reviews do not simultaneously summarize the studies on cold and heat storage in SACSs, which is needed to discuss the diversity of latent thermal energy storage system (LTESS) designs for different application scenarios. Moreover, most studies emphasized the role of PCM in the latent thermal storage unit, but ignored the PCM container.

This paper aims to review the enhancement methods and current status of available PCMs and their containers from the heat (including thermal power and heat recovery storage) and cold applications of LTESSs in SACSs. The aspects emphasized in this review are described as follows:

- Material selection and performance optimization of PCM and its container

- Economic evaluation of enhanced technology and LTESs.

The outline of this paper is as follows:

1. Section 1 briefly summarizes the contributions and limitations of other reviews on LTESs in SACSs.
2. Section 2 presents applicable PCMs, and their selection methods and improvement strategies.
3. Section 3 describes the categories, key design considerations, and enhancement strategies of latent thermal storage containers.
4. Section 4 discusses the use of LTESs in SACSs with respect to heat and cold storage.
5. Section 5 discusses the hybrid enhancement of PCM and its containers, and the economic evaluation of LTESs in SACSs.
6. Finally, Section 6 reports the main findings of this paper and suggestions for future research.

2. PCMs for solar air-conditioning systems

PCMs used in SACSs have the potential to store energy during off-peak periods and reuse the energy during the peak times, thus reducing and transferring peak loads [33]. PCMs have been used for thermal storage since the 1880s [34]. Since then, most studies focused on finding PCMs with improved properties [35]. In this chapter, the selection method and improvement for PCMs in SACS are reviewed.

2.1 Applicable PCMs in LTESs of SACSs

Solid–liquid PCMs are widely used in SACS owing to their low phase transition temperature and small volume change. Solid–liquid PCMs can be further divided into organic, inorganic, and eutectic PCMs, as shown in Figure 3. Their properties are shown in Table 1. The ideal PCMs for SACS should have the properties shown in Table 2. Unfortunately, very few PCMs satisfy all the requirements. Therefore, it is necessary to find the best suitable PCMs considering the requirements of the specific system. This selection process forms the core of effective LTES design. In general, the PCM is mainly selected based on the required melting temperature range. Table 3 shows the suitable temperatures for cold and heat storage levels in SACSs. However, it is not sufficient to determine the PCM only based on the melting temperature. Thermal conductivity and specific heat are considered to ensure a high storage density and high efficiency of the system [27]. The volume change rate of PCM should also be considered to optimize the system design [28, 31]. Table 4 shows the PCMs considered for use in the LTES field in SACSs.

Place Figure 3 here

Place Table 1 here

Place Table 2 here

Place Table 3 here

Place Table 4 here

2.2 Selection methods

The traditional selection method involves the use of charts to compare and select the thermophysical data obtained from a literature search. However, this method has many disadvantages. Because a large number of PCMs are available or under development for SACs, it is difficult to find the best suitable PCM. Because of the lack of suitable and complete thermophysical data, manual selection makes the process time-consuming, difficult, and error-prone. In contrast, the selection can be more comprehensive, user-friendly, faster, and accurate by using a database [58]. A database also makes it easier to find and evaluate materials with similar properties that can also be considered for the task.

Material databases can be divided into offline and online databases. In the 1970s and 1980s [59], storage media mainly consisted of CD-ROMs when computers were used. Hence, numerical offline databases such as Mat. DB and CMS systems were common at that time [60]. With the availability of internet, modern databases are mostly accessed online. The more famous commercial databases are MatWeb and NIMS. Refs [61] and [62] summarized a large number of databases that can be used to select PCMs.

However, dozens of potential materials may still be available for a given scenario. Therefore, it is necessary to rank and analyze the candidates using a consistent evaluation system. Because each candidate has several measurable indicators, this type of selection problem is more suitable for multicriteria decision-making (MCDM). MCDM is divided into multiobjective decision making (MODM) and multiattribute decision making (MADM) [62]. A popular MODM tool is the Ashby method [63]. Because of the limitation of the used principle, the Ashby method is mainly used for the preselection of PCMs [62]. Commonly used MADM methods for PCM selection include both the hierarchical analysis method (AHP) and ranking performance technique (TOPSIS) [63-67]. Xu et al. [68] found the most suitable PCM for a solar lithium bromide absorption refrigeration system using MADM in combination with AHP and TOPSIS by targeting a specific temperature range and considering the volume constraints for PCM. Yang et al. [69] introduced a comprehensive evaluation index model that uses both AHP and the entropy information method. The group also used TOPSIS to select the optimal PCM for a ground source heat pump system. The model considers the individual design and is very flexible. MCDM is an economical and convenient alternative technology to sort and filter PCMs.

Although electronic PCM material selection represents an important step forward, there is still room for improvement. First, the organization responsible for the database should update and supplement all the material data sufficiently and frequently. Second, the software should also provide information about possible material handling methods, defects, previous uses (examples), and possible future uses, in addition to basic physical properties. However, the complete collection of data depends on the software developer.

2.3 Selection of PCM strengthening methods

Most of the PCMs discussed above have some disadvantages that limit their use in SACSs, such as a low thermal conductivity and supercooling. These problems directly affect the storage and release efficiency of PCMs, thus limiting the long-term operation of the system. Therefore, a PCM should be optimized to achieve good heat storage performance. Table 5 shows some of the problems associated with PCMs and the corresponding solutions. Table 6 shows the PCM enhancement methods applied to LTESSs in SACSs. Table 6 reviews the control variables, evaluation indicators, recommended parameters, and promotion effects of the improvement methods reported in the studies.

Place Table 5 here

Place Table 6 here

To improve the thermal performance of LTESSs, extensive studies have been conducted on the thermal performance enhancement technology of PCMs in the past decades [28-31]. As shown in Table 6, the heat transfer enhancement method used in PCMs is used mainly to reduce the thermal resistance of PCMs by adding high thermal conductivity materials to the PCM, such as expandable graphite [72, 93, 94], nano-scale metal [75] and metal oxide [91].

Metals are considered to be good additives in the medium-temperature PCMs owing to their high thermal conductivity. However, metals easily react with PCMs. For example, nickel is incompatible with paraffin [95]. The thermal conductivity of expanded graphite and carbon fiber exceeds most metals. At the same time, they have excellent corrosion resistance and chemical stability. Therefore, the addition of graphite and carbon fiber additives in corrosive inorganic PCMs can play a two-fold role [93]. Oya et al. [72] compared the thermal properties of erythritol with expanded graphite, spherical graphite, and nickel particles. The theoretical effective thermal conductivity of 15 wt% expanded graphite and spherical graphite increased by about 640% and 210%, respectively. The strengthening effect of 15 wt% nickel particles is close to that of spherical graphite of the same concentration. The results show that graphite additives have a higher enhancement effect on the thermal performance of PCM than metal additives. However, the manufacturing technology of graphite additives is more complex than metal particles [73]. Nanoparticles have the potential to greatly improve the thermal conductivity of PCMs. This is because the addition of solid particles enhances the thermal conductivity of PCMs. In addition, the small-size effect of nanoparticles causes microconvection between the particles and liquid. However, a high concentration (0.05 wt%) of nanoparticles will hinder the convection heat transfer in the late melting stage of PCMs [92].

In summary, in quantitative studies of high thermal conductivity additives, there is a common question worth discussing—what is the appropriate quantity? For example, the addition of a metal powder can double the thermal conductivity of PCM. However, the density of metal is large, and the more the components, the more obvious the weight gain of the container, imposing a burden on the installation of the system. At the same time, the increase in additives will also increase the cost of system. Therefore, considering the size of the system, balancing the cost and benefit

of thermal storage performance brought by high thermal conductivity additives can be more effective for engineering applications of LTESSs. This study [96] demonstrated an economic analysis of improvement technologies. The author measured the cost of expanded graphite in the latent heat storage unit. The results show that the use of expanded graphite can save steel and reduce the initial investment cost by more than 20%. Future studies can measure the long-term operating benefits of PCMs with strengthening strategies based on cost.

3. PCM storage containers for SACS

Unlike conventional heat exchangers, PCM storage containers have both fluid pipes and PCMs inside, enabling thermal transfer and storage concurrently. The successful application of PCMs also depends on the development of containers. Achieving the high thermal storage efficiency on the premise of meeting the cold or heat demand is the goal of LTESS design. The thermal storage efficiency of an LTESS is related to the melting and solidification characteristics of PCM that are mainly affected by the heat transfer mechanism (conduction and/or convection) [97]. The geometrical structure and gravity effect of a PCM container will affect the heat transfer mechanism of PCM, which can be quantified from the melting time and the motion of solid–liquid interface during the phase change. Therefore, the design of a properly structured PCM container is critical for improving the thermal storage efficiency of LTESS. In addition, the thermal conductivity of material of PCM container also affects the thermal conduction of phase change. And the corrosiveness and thermal stress of the material also affect whether the conduction can operate normally at a suitable temperature. This chapter mainly introduces the classification of PCM containers, selection suggestions for their materials and geometric structures, and the thermal transfer enhancement on the container side.

3.1 Classification of containers

The type of PCM storage containers varies with the operating temperature range [98, 99]. For low- and medium-temperature solar energy utilization, PCM storage containers for SACS can be divided into bulk storage and (small volume) encapsulation storage. Bulk storage is similar to heat exchangers with respect to the structure. It can be further divided into the following: plate, multitube, concentric tube, shell-and-tube, spiral tube [100]. The aim of structural diversification is to increase the heat transfer efficiency by increasing the heat transfer area. It should also be considered that the volume change of a PCM for bulk storage causes thermal stress, causing the deformation of equipment. Encapsulation storage refers to the arrangement of encapsulated PCMs in a tank in a particular way. The PCMs are encapsulated using hydrophilic polymer capsules as shell-covered core [101]. Encapsulated PCMs are generally used for microencapsulation and nanoencapsulation with diameters smaller than 1 cm and 1 mm, respectively [102]. The methods to form encapsulated PCMs vary depending on the material wrapped. Emulsion, *in-situ* polymerization, interfacial polymerization, electroplating, sol–gel processing, and mechanical packaging methods can be used for both inorganic and organic PCMs [103]. In addition, organic PCMs are suitable for the encapsulation of suspension

polymerization, dispersion, coacervation, supercritical CO₂, spray drying, electrostatic encapsulation, and the one-step method [104]. Encapsulation storage can also enhance the thermal performance of PCMs. It can produce a larger heat transfer surface and solve the volume–stress problem of PCMs; however, it is expensive [102].

3.2 Container design considerations

3.2.1 Materials

Similar to the ideal properties of PCM, PCM storage containers have been suggested to have the following desirable properties [105]: 1) compatibility with the PCM in bulk, 2) high stability, 3) high strength, 4) high-temperature resistance, 5) sufficient flexibility to resist thermal stress caused by volume expansion, and 6) low cost.

In practice, it is difficult to find materials that can fully satisfy all the requirements. Moreover, container materials are typically selected after the PCM is selected. Only a small number of containers are usually compatible with a specific PCM. The selection of final container material should be considered in both system requirements and costs. The typical selection process relies on the experience of experts and opinions about past applications, making the process very subjective.

For bulk storage, metal is the most common container material. Research groups led by Cabeza [106], Farrell [107], and Moreno [108] investigated the compatibility of PCMs with steel, stainless steel, aluminum, brass, and copper in the short to long term. Current studies indicate that stainless steel is suitable and recommended for all studied PCMs [109]. Regular steel shows good compatibility only for specific salt mixtures such as NaCl–NaNO₃ [109]. Steel shows varying degrees of corrosion when exposed to other salt mixtures such as Zn(NO₃)₂·6(H₂O), LiCl–LiNO₃–NaNO₃, and KCl–LiCl [110]. Therefore, regular steel is generally not recommended as a PCM container material [82]. Covering hydrated salts with aluminum can cause severe corrosion. Although aluminum soaked in fatty acids shows signs of corrosion, it does not destroy the sealing structure [111]. Therefore, aluminum can be a suitable container for PCMs. Copper and brass are suitable container materials for paraffin wax, but the encapsulation of fatty acids and hydrates requires anticorrosive treatment [107, 111]. In addition, nonmetallic materials have been developed; they are not corrosive but flexible. These materials are mainly plastics [112] such as acrylic and high-density polyethylene [113, 114].

The most commonly used capsule materials for microencapsulation and nanoencapsulation are organic polymers such as melamine–formaldehyde resins [115, 116], urea formaldehyde resin [117], phenolic resin [118], polystyrene [119], and arabic gum [120]. The mechanical strength of organic shell increases the structural stability of microcapsule system. However, its low thermal conductivity, toxicity, and flammability lead to a hysteresis for the thermal response and heat transfer. This limits

the use of microcapsules with organic shells [121]. Inorganic materials for capsule walls include CaCO_3 [122, 123], SiO_2 [1124, 125], TiO_2 [126, 127], and ZnO [128]. Silicon is often used for the inorganic shell of microcapsules. However, because of the diffusion and decomposition of PCMs at high temperatures, the poor mechanical strength of silicon shell often leads to the cracking of microcapsule [125]. Therefore, inorganic materials with a high mechanical strength, a high thermal conductivity, and low cost are typically used for capsules. Examples include CaCO_3 and $\text{SiO}_2\text{-TiO}_2$ [129]. Because of the complementary advantages of inorganic materials and organic macromolecules, a suitable combination of organic and inorganic materials could be the future trend for encapsulation.

3.2.2 Geometric parameters

(1) Bulk storage

Both size and shape, i.e., geometric parameters, of latent thermal storage containers (LTSCs) considerably affect the heat transfer mechanism and melting behavior of PCMs [130, 131]. Current commonly used PCM container shapes are rectangular enclosures [132, 133], circular cylinders [134], and annular cavities [135, 136]. Zivkovic and Fujii [137] proposed a computational model for analyzing the isothermal phase transformation of PCMs encapsulated in a single container. The model neglects the conduction inside the PCM in the direction of heat transfer fluid (HTF) flow, thermal resistance of container wall, and effect of convection. They also compared the heat transfer properties of rectangular and cylindrical LTSCs through the model. The results show that the melting time of a PCM in a rectangular vessel is almost half of that in a cylindrical vessel, given both have the same initial volume and heat transfer area, i.e., a rectangular container is more beneficial for achieving a high thermal storage efficiency of LTES. However, this conclusion only applies to the case where the system uses a flat thin-walled container. However, because a rectangular container has a melting dead angle in the late stage of PCM melting, it has been proposed to transform the rectangular shape into a wedge shape. Through enthalpy–porosity model simulation, the wedge scheme can effectively improve the vertical temperature distribution and enhance the convective heat transfer in the container in the late melting stage of PCM, reflected in the increase of instantaneous Nusselt number [138]. The heat storage time is shortened by more than 20% compared to the rectangular unit with the same heat source area. Hou et al. [139] experimentally analyzed the thermal storage performance of cylindrical and annular containers. When filled with the same mass of sodium acetate trihydrate, the thermal storage time of the annular type is 61.8% shorter than that of the cylindrical type. This is because the annular container has a larger surface area and faster heat transfer rate than the cylindrical container. To make the convective heat transfer dominant in the late stage of melting, an inverted cone scheme is used for the modification of cylindrical units. In the melting stage, the inverted cone unit can accumulate a large amount of PCM liquid at the top, thus forming a stronger natural convection than the cylindrical unit. This accelerates the melting rate and thus also accelerates the energy storage of the system. The experimental study by Seddegh et al. [140] found that the

inverted cone unit can store 10% more energy during charging than the cylinder unit.

PCM melting in a finite closed container involves contact with the heat source at the initial melting stage and is generally dominated by heat conduction. In the later stage, with the melting proceeding, the amount of liquid phase gradually increases, and the difference in solid–liquid density enhances the liquid buoyancy lift, thus increasing the effect of natural convection. Therefore, many dimensionless numbers such as Nusselt number (Nu), Grashof number (Gr), Rayleigh number (Ra), and Prandtl Number (Pr) related to natural convection have been introduced to study the PCM melting characteristics in containers of different structures and geometries. For rectangular containers with a single-sided fixed heat source area, a lower aspect ratio (ratio of fixed width to variable height) has a positive effect on the heat storage efficiency of system. This is because on one hand, the amount of PCM present in the device decreases as the aspect ratio decreases, and the heat storage time is naturally shortened. On the other hand, the average Nusselt number in the container increases with the decrease in aspect ratio, and the natural convection is strengthened, accelerating the melting rate of solid phase [138]. However, the contribution of reducing the aspect ratio to the heat storage efficiency of system is limited. Hu et al. [141] calculated the limit of aspect ratio of a rectangular container filled with *n*-octadecane to be 1/8 from the enthalpy model. When the value is lower than the limit, the heat storage time remains fixed. For the wedge unit, the geometric factor that mainly affects the heat storage efficiency is the ratio of upper and lower sides. Because of the sharp angle of wedge shape, an excess large ratio of the upper and lower sides will form a more severe melting dead zone. Therefore, an optimum ratio exists for the upper and lower sides of wedge unit. Hu et al. [142] simulated the melting of octadecane in a wedge container through enthalpy–porosity method. The results confirmed that the optimum ratio of side length is between 5 and 6; therefore, 5.5 is recommended as the design reference for the aspect ratio of wedge unit. The melting of PCM in a cylindrical container is similar to that in a rectangular container. Similarly, the geometric factor affecting the heat storage efficiency of a cylindrical phase change unit is the ratio of the bottom diameter to the cylinder height. For the same reason, reducing the aspect ratio of a cylinder is beneficial for increasing the melting rate and decreasing the charging time [131, 143, 144]. In the annular unit, eccentricity is an important geometric factor. Because of eccentric setting, the upper space of unit increases, allowing more PCM to be located in the area where natural convection can work, and the natural convection is stronger. Therefore, this has a positive effect on improving the melting rate and reducing the related charging time. Because of natural convection, the melting rate of PCMs in an eccentric annular vessel is faster than that in a concentric annular vessel [136,145-147]. Hu et al. [148] studied the heat transfer of lauric acid in an eccentric annular unit with a characteristic size of 20 mm. The range of studied eccentricity varied from 3 mm to 8.5 mm. The group found that 7–8 mm is the optimal eccentricity.

(2) Encapsulation storage for a small volume

Apart from the well-known spherical shape, capsules can be cylindrical, tubes, or plates [149]. A sphere can form strong natural convection and heat storage and release

efficiency owing to its simple structure and large ratio of volume to surface area [150]. Therefore, a spherical shape is the common shape for encapsulation [151]. However, parameters such as particle size, core-shell ratio, and shell thickness directly affect the durability and thermal performance of capsules [101, 152, 153]. Hence, they are important design factors for capsules. A general valid guideline is that the smaller the particle size of microcapsules, the better the structural stability and thermal performance of a heat storage system. This is because the melt fraction in a small capsule is high, resulting in a smaller thickness of melt layer near the capsule wall. This leads to a smaller thermal resistance in the capsule. On the other hand, it also provides a larger surface area of contact between the PCM and capsule wall. Because of a short heat transfer path, when the capsule radius is small, the energy is charged at a higher rate [154]. Wei et al. [151] studied the thermal properties of stainless steel-paraffin microcapsules with four different diameters (2.0, 3.0, 4.0, and 5.0 mm). The results show that the exothermic time decreases with decreasing particle size. Alvarado et al. [155] recommended that the diameter of microcapsule PCM (mPCM) should be 2–10 μm to ensure durability and high mechanical strength. However, the diameter of mPCM should not be too small, as this can cause supercooling [156, 157]. In addition, with the buildup of smaller-diameter capsules in the tank, the flow resistance increases substantially. Consequently, the turbulence and momentum transfer are suppressed, resulting in reduced heat transfer efficiency. Based on these results, it becomes clear that smaller-diameter sizes are preferred. However, it is necessary to add nucleating agents or to optimize both the shell composition and structure of mPCMs to avoid supercooling. Refs [104, 158] provide more detailed reviews of design parameter studies on encapsulated PCMs.

In summary, a rectangular container is still the preferred container for bulk storage because of its high efficiency and simple manufacturing process. Some of the improved schemes involving rectangular and cylindrical containers such as wedge and conical units have improved the heat storage efficiency by more than 10%. However, economic analysis of these schemes is lacking, and it is difficult to determine the size of an appropriate system for these schemes. Furthermore, the datasets of container materials should be collected and organized similar to the PCM database because of the large number of container materials and related design parameters. The recommended container materials should be provided directly on the PCM selection page. PCMs and their container materials can be thoroughly evaluated using a specialized software, benefitting the design optimization for LTESs of SACSs. According to the literatures mentioned above, it is clear that environmental friendliness is rarely considered in studies of container material selection, which is a different process than PCM selection. Eco-friendly PCMs from natural sources such as coconut oil are rarely used and developed for SACSs. PCMs or containers derived from bio-originated materials still have a high potential for improvement and new discoveries.

In addition, it is concluded from the abovementioned studies that the optimization of geometric factors and container shapes involves improving the heat transfer mechanism of PCMs (heat conduction in the early stage of melting and convective heat transfer in the later melting stage). Therefore, enhancing natural

convection or contact area is a key breakthrough point in developing new configurations and designing the geometric parameters of containers. Furthermore, the heat transfer mechanism within the container can be described by flow-related dimensionless numbers such as Nu and Ra; the geometry of container can be optimized for enhancing the heat transfer mechanism. Therefore, in the future studies on PCM container optimization, the dimensionless number related to the heat transfer mechanism can be used to establish the relationship between the structure and geometrical factors of container to achieve the design and selection of PCM containers, instead of a large number of simulation work.

3.2.3 Effect of container design considerations on the performance of PCM integrated solar air conditioning system

From the above descriptions in Sections 3.2.1 and 3.2.2, it can be seen that most studies have contributed to the promotion of heat storage efficiency by design optimization of PCM containers. And these studies mainly focus on experimental and simulation studies of the thermal characteristics of single thermal storage unit. Relatively speaking, there are few studies on the system performance evaluation of LTESs of SACSs by geometrical optimization of PCM containers. In the field of simulation research, Noro et al. [159] used TRNSYS software to simulate the annual energy performance of solar single-effect absorption refrigeration systems with latent cold and heat storage (heating season: November 1st - April 15th; cooling season: June 1st - September 15th). The system was located in a three-story building of 230 m² in Rome. The study evaluated energy efficiency of the whole SACS for different container capacities (500-1000, 1000-2000, 2000-3000 L). And fossil primary energy consumption (FPEC), primary energy saving (PES) and solar ratio (SR) were used as the evaluation index of the system. Obviously, the whole system is expected to consume the lowest fossil energy and be able to store more solar energy to satisfy the demands of heat storage and cold storage. Therefore, in order to obtain the PCM container capacity with the optimal system energy efficiency, the lowest FPEC, the highest PES, and the highest SR are expected. In the simulation results, the PCM container capacity of the 2000-3000 L was the best; it shows that increasing container capacity has a positive effect. The study found that the design of the PCM container plays an important role in system performance, but only simply compared the difference of energy benefits brought by storage capacity. Pintaldi et al. [160] simulated the annual system performance of a solar three-effect absorption refrigeration system with consideration of geometric parameters in the container and collector design. The collector area (1-4 m²/ kW) and heat storage time (30 minutes, 1, 3, and 5 h) were considered as the representational parameters. Heat storage time was used to calculate the diameter and height of the PCM container, and the number, diameter and length of inner tube. Basically, the smaller the storage time represents the smaller the container size. The pros and cons of the system are mainly evaluated based on SR, heat loss and energy storage efficiency. The results show that short storage time (0.5 h) can lead to a high storage efficiency (more than 98%) because of the low heat loss. But at this time, the storage efficiency hardly changed with the increase of the collector area. At a high storage time (5 h), the storage efficiency was increased by nearly 1% with the increase of the collector area. All combinations of

collector area and storage time can enable the system to achieve a SR of more than 0.5. And with the increase of collector area and storage time, the SR also increased, the highest value was nearly 0.94 when the collector area and heat storage time were 4 m²/kW and 5 h.

In addition, a few scholars tested the performance of thermal storage equipment by setting up an experimental platform of SACSs. In a series of studies by Zhai et al., [26, 161] a mathematical model of the charge/discharge process of the cold-storage capsule unit was established, and the system performance with the appropriate cold storage unit parameters was evaluated by the experimental platform of a solar adsorption air-conditioning system. At first, the authors established the equation for the phase change heat transfer process of the cold-storage capsule unit by the enthalpy method. The influence of the capsule wall material, thickness, and diameter of a cold storage unit on the cold storage capacity and the cold storage rate was theoretically analyzed by the equation. The results show that the cold storage capacity and cold storage time increase with the increase of the capsule diameter. A capsule wall material with a thermal conductivity higher than or closer to the PCM was suitable for engineering applications. In addition, under the same thermal conductivity of capsule wall, the cold storage time increased linearly with the increase of the wall thickness. Based on theoretical calculations results, the cold storage capsule with polyethylene shell, a wall thickness of 2.5 mm, and an outer diameter of 35 mm and 70 mm were combined and arranged in a cylindrical bulk container. The day test was conducted during the summer in Shanghai. It is worth noting that the main concerns of the experiment were the charge/discharge capacity and the thermal comfort of the user side during the discharge process. The experimental results show that the charge capacity was 1016.1 kJ, the discharge capacity was 942.8 kJ, and the cold loss was 7.11%. In addition, the average indoor temperature during the system discharge process was 26.2 °C.

In summary, it can be seen that only the optimal container parameters in the theoretical analysis can be verified in the experimental study, because of the long test cycle and high cost. Compared to experimental studies, simulation studies are worthy of advocacy. Because it can reliably compare the whole system operation and energy performance through geometric parameters and internal layout in the early stage of container design. However, most of the simulation studies in the field of SACS have mainly used PCM capacity instead of complex container parameters to analyze its impact on system energy efficiency. It cannot show the relative importance of the wide range of container design parameters to system performance. In addition, the comprehensive evaluation through SR and energy storage efficiency can select the appropriate single factor domain in the PCM container design, but it is difficult to obtain the optimal value under multiple design factors. From this perspective, we propose to introduce genetic algorithm, particle swarm optimization and other multi-objective optimization methods in the PCM container design of SACSs. These algorithms have not been fully developed yet in the field of LTESs of SACSs, but they have been successfully applied in the PCM container design of solar household hot water systems [22, 162, 163] and industrial water waste heat recovery systems [164].

3.3 Selection of enhancement methods for containers

Each container has a unique structure and requires a different optimization method. Table 7 shows the corresponding strengthening techniques and specific selection criteria for different containers in reported studies.

Place Table 7 here

3.3.1 Adding fins on the container side

To enhance the heat transfer for bulk storage, fins can be added to increase the heat transfer area. The use of fins in thermal storage device design is very common [184, 185]. This is probably because the technology needed to configure fins is simple and easy to implement. Common types of fins are longitudinal/rectangular [186], circular/annular [187], and plate fins [188]. Among these fins, rectangular fins are used the most owing to easy fabrication and efficient heat transfer. Agyenim et al. [189] compared the thermal performance of horizontal concentric tube storage devices with three different structures (finless, circular fins, and longitudinal fins). The results show that storage efficiency of total amount charged of longitudinal fins was 70.9%, 9-20% higher than the other two structures. Thus, longitudinal fins perform the best. Zhai et al. [190] developed a refrigeration unit for high-temperature solar cooling systems. The effects of structural parameters such as spacing and the number and height of rectangular and circular fins on the cold storage performance were studied experimentally and numerically. The results show that compared with the finless unit, the phase transition time for a rectangular fin unit is reduced by 58.2%, 2 times higher than that for an annular fin unit. With respect to fin design, three structural parameters are important: width, spacing, and thickness [191]. Increasing fin thickness and width or decreasing fin spacing significantly shortens the phase transition time [192]. In addition, fins should be made of highly conductive metals to ensure good heat transfer.

3.3.2. Improving the internal structure

LTSCs could gain more thermal performance benefits than fins by improving the internal structure [193]; for example, the internal structure of LTSCs can be enhanced via the flow direction and arrangement of PCMs and inner tubes. In multitube LTSCs, increasing the number of inner tubes can effectively increase the efficiency of heat storage. Mehdi et al. [194] studied the influence of number of inner tubes on the melting and solidification rate of RT35. A higher number of internal tubes shortens the phase transition time. The melting time of LTESs with four internal tubes was 41% shorter than that for one internal tube. In addition, the right arrangement of inner tubes can also facilitate heat transfer, even with a few inner tubes. Pourakabar and Darzi [195] studied the influence of inner tube arrangement on the phase change rate of LTESs. The results show that the melting and solidification rates for vertical two-tube arrangement in the ellipse container are similar to those for four-tube diamond arrangement. In LTSC, the flow direction of working fluid is divided into parallel flow, crossflow, and counterflow. Generally, the use of counterflow devices

can produce a better heat transfer. Belusko et al. [193] compared the thermal performance of parallel flow and counterflow in LTSCs. They found that the heat transfer was better for a countercurrent device. The volume of redundant PCMs in LTSCs with a parallel flow device is almost four times that with a countercurrent device. This significantly affects the cost of thermal storage system.

The layout of PCMs in containers is also a common method to improve heat transfer. Lafri et al. [196] experimentally optimized the position of PCMs in a tank. They designed two different structures for their study. Structure A integrated paraffin wax directly into the side of the tank, whereas structure B had paraffin wax in the center of the tank. It was found that the melting time of PCM with structure A was almost twice as long as that for structure B. Similarly, when the capsule was placed in a cylindrical container tank, the number of layers and the number of capsules per layer severely affect the heat transfer [29]. Heat transfer can also be enhanced using a combination of different PCMs with different melting points. Yang et al. [183] designed a LTESs containing a spherical capsule packed bed with three types of PCMs. They conducted a numerical study on the thermal storage performance and compared the results with traditional single-type LTESs. The results indicate that the designed system has a 65% exergy efficiency, which can be higher than that of single-type in theory.

3.3.3 Modification of capsule material

The capsule material can also be modified to improve the heat transfer. All capsule materials suffer from a low thermal conductivity, especially organic capsule materials. To solve this problem, some researchers added metal coatings [197], expanded graphite [198, 199], graphene oxide [200, 201], and nanotubes [182] to the capsules. Compared to ordinary mPCM with the same concentration, the heat transfer coefficient of mPCM slurry with a metal coating increased by more than 10 % [170]. Moreover, the thermal conductivity increased with increasing metal coating coverage until the capsule was fully covered [179]. Wang et al. [180] added 10% and 20% expanded graphite to the shell of a melamine–formaldehyde resin; the thermal conductivity of microcapsules increased 10 times and 22 times, respectively. Wang et al. [181] also increased the thermal conductivity of microcapsules by adding graphene oxide to the silica shell. The experimental results express that the thermal conductivity of microcapsules with 1wt% graphene increased by 193%, compared with the ordinary silica shell.

4 Thermal storage technologies for solar air-conditioning

4.1. Thermal storage use

4.1.1 Thermal power applications

In solar absorption and jet air-conditioning systems, LTESs provide the heat source to heat a medium water driving regenerator and steam ejector. Poshtiri and Jafari [202] reported a PCM unit in a solar adsorption system that stores energy in the

daytime to drive the adsorption cooler at night. The PCM unit stores 409 kg of fatty acid to drive the charging of 10:00-16:00 in the day and the discharging of 22:00-8:00 in the night. The study simulated 24-h solar adsorption cooling in a room of $8.0 \times 8.0 \times 3.125 \text{ m}^3$. The results show that the application of PCM reduces the nighttime auxiliary energy consumption by ~31% compared to systems without PCM. However, even with the application of PCM, the entire solar adsorption system consumes 3.28 times more energy than a conventional split-type air-conditioning system.

In solar desiccant air-conditioning systems, LTESs represent a heat source of regenerated air at a low solar intensity. A schematic diagram of such a system is shown in Figure 4. A PCM heat storage tank is mostly an independent unit connected with a collector system. Generally, the PCM unit serves two purposes: (1) preheating of the regenerated air before it enters the solar collector. (2) The PCM is heated by hot air that is discharged from a desiccant wheel or a solar air collector. Kabeel et al. [203] compared the energy saving performance of desiccant air-conditioning driven by pure electric heating (A type), electric heating + solar heating (B type), and electric heating + PCM + solar heating (C type). In particular, C type had the design of two serpentine loops (see Figure 4 (b)) in a paraffin-filled heat storage tank to transport the regenerated air. The PCM unit was designed to store energy from 10:00 to 17:00 the day before the workday and release energy from 10:00 to 22:00 the second day. The results show that compared to purely electrically driven type, the energy saving rate of C type is up to 75.82%, almost four times that of B type. In addition, an economic analysis of the three systems was also carried out. According to the price of Egyptian energy market, the C type has the highest total fixed cost, twice that of A type, but the total annual operating cost of C type is 626 LE, which is about a quarter of A type. This shows that the application of an PCM unit in the system can provide great energy saving potential for long-term operation. To minimize the use of municipal electricity, Ren et al. [204] integrated a solar air collector and photovoltaic collector to drive a desiccant cooling system and an auxiliary heating equipment. They also designed a PCM TES unit to satisfy the thermal demand of regenerated air, consisting of several parallel PCM boards. The group designed a bypass in the PCM unit to avoid the overheating of regenerated air (see Figure 4 (c)). The new design applied for a 66 m^2 solar-powered room was simulated with the experimental data provided by Lopez et al [205]. At regenerative temperatures of 60°C , 65°C , and 70°C , the system achieved a humidity satisfaction rate of over 80%. When the regeneration temperature was 60°C , the regeneration coefficient reached 100%. This proves the feasibility of this new system without municipal power supply. Table 8 shows the possible options for power solar air-conditioning. Table 8 also shows the operation effect of the system mentioned in the literature.

Place Figure 4 here

Place Table 8 here

Among the PCM heat storage applications, we found that most PCM tanks are connected behind solar collectors as separate units. In fact, the design principle of SACSs is to facilitate the use of simple and compact equipment to produce an economic system [209]. Therefore, PCM TES units, which can be integrated with

collectors as well as adsorption units or regenerators, are valuable for both research and commercialization. Although this integrated design has attracted the attention of some researchers, it has failed to enter large-scale production. Mohammadreza et al. [206] designed an integrated component consisting of an adsorption element, a collector, a PCM regenerator, and a combined condenser/evaporator under a vacuum-containing glass case. The adsorption element is a thermochemical storage device, which achieves desorption and adsorption through a LiCl-H₂O solution. The PCM regenerator is mainly used to provide instantaneous cold and heat sources for the adsorption module. The results of both experiment and simulation indicate that this new solar adsorption air-conditioning system is feasible, and the average coefficient of performance (COP) of the system can reach 0.36 (cooling) and 0.42 (heating).

4.1.2 Heat recovery applications

An air-conditioning system produces condensed heat far greater than its cooling capacity [210]. This heat is emitted directly into the environment, thus wasting energy and producing local thermal pollution [211]. Hence, separating the heat of condenser from the refrigeration cycle of conventional air-conditioning system can extend the heat rejection of condenser to compressor downtime, thus increasing the heat transfer for the condenser and providing a lower condensation temperature [212-215]. PCMs are integrated with evaporators in solar absorption systems. This enables the use of dry cooling systems in place of a wet cooling tower. Additionally, it reduces the water consumption, decreases cleaning needs and the risk of bacterial growth, and minimizes the requirements for a cooling system. Helm et al. [39] designed a solar absorption system with a PCM unit combined with a dry cooler instead of a wet cooler. During the refrigeration operation, a portion of the waste heat of the cooler was buffered, so that the cooler works under the peak load and the coolant temperature is lowered. At lower ambient temperatures such as nighttime or nonpeak loads, the stored waste heat is discharged. At this time, the auxiliary energy source is applied during the nonpeak operation, and thus electricity is consumed. However, because of the policy of ladder-type electricity prices, the overall cost of municipal electricity is balanced, and the load distribution is more uniform. At runtime, the PCM unit stores ~50% of the daily waste heat under hot ambient condition (32 °C) and releases heat from PCM units below 20 °C. In addition, the PCM unit has 10 times volume storage density, thus reducing the cost and size of the entire system compared to the water system.

In addition, the waste heat obtained from the high-concentration photovoltaic (HCPV) module was significant, and the heat flux increased. Therefore, effective cooling is needed to ensure that the module has the right temperature needed for a normal operation of the photovoltaic power generation system. In the absence of a PCM unit heat recovery system, the waste heat generated by the photovoltaic system can only be discharged into the environment. PCMs can be combined with a photovoltaic heat recovery system to increase the energy efficiency of system and save municipal electricity. Zhang et al. [216] designed a PCM unit to absorb the wasted heat generated by the photovoltaic module to drive an adsorption air-conditioning unit or a hot water system. Circulating water stores the waste tropical to PCM heat

recovery units during the day. When the photovoltaic module stops working at night, the circulating water heated from the PCM unit is transported to the adsorption air-conditioning module or the hot water system. When the waste heat generated by the photovoltaic module is insufficient for heat storage, the heated circulating water is sent to the PCM unit for heat storage. The author developed a theoretical COP calculation method for the system. In theory, the COP is significantly improved compared to a photovoltaic air conditioning system without PCM units. Unfortunately, the authors did not make a quantitative comparison between the two. Table 9 shows the possibilities for heat recovery.

Place Table 9 here

In summary, the application of heat recovery is relatively less compared to thermal power applications in LTESs of SACSs. This is probably because the residual heat in SACS is relatively small, and the use of water as a heat storage medium is more cost-effective than PCM. At the same time, it is difficult for the solid–liquid PCM unit to extract waste heat directly, generally through water or other heat transfer medium. Therefore, the layer-by-layer heat transfer between waste heat, water, and PCM results in heat loss. In addition, solid–liquid PCM units are limited in cost and heat storage time; they are more suitable for day-based and unstable waste heat commonly found in small independent SACSs. For large-scale SACSs that require long-term heat recovery, the application of latent heat storage systems is limited. Therefore, the economic analysis of latent heat recovery systems and the quantification of system COP enhancement should be strengthened to identify suitable application objects.

4.2 Cold storage applications

Latent cold storage enables high energy density, facilitating continuous cooling and reducing the volume of cold storage equipment. These advantages stimulated research in this field. Diaconu et al. [220] proposed a mathematical model for a solar ejector cooling system with a PCM cold storage unit. The energy consumption of an office building was simulated. The results show that the COP of the system with PCM refrigeration unit is 80% higher than that without PCM unit. Chen et al. [221] conducted an experimental study on the thermal performance of a solar ejector cooling system that uses a cylindrical PCM tank. Any remaining energy was stored in the PCM unit and used to maintain the normal operation of the system when the ejector was not running. The results indicate that a PCM cold storage can help maintain a constant COP. They also suggested that the use of PCM cold storage in a solar ejector cooling system is promising. Allouche et al. [25] used TRNSYS to develop a dynamic simulation model for an ejector cooling system that was integrated with a PCM unit. The group strongly recommends the use of latent cold storage for ejector solar cooling. The maximum COP in the simulation is 0.193, and the monthly average COP is more stable and almost double than the system without a PCM unit. However, only relatively small PCM thermal storage tanks should be used for sun-rich areas. A large thermal storage capacity can add thermal inertia and initial system cost. Zheng et al. [222] studied the effect of microcapsule PCM on the daytime operation of a solar compression air-conditioning system in a laboratory scale. The PCM unit was

connected to the refrigeration unit for storing cold. In the hourly energy consumption record from 8 a.m. to 17 p.m., the system with a PCM unit saved more than 20% energy compared with the electrically driven air-conditioning system. The maximum energy saving of a system with a PCM unit could save 30.5% at 13:00. Table 10 shows the possibilities for cold storage.

Place Table 10 here

5. Discussion

From the abovementioned literatures, it can be concluded that the development of LTESs in SACSs (not including the system control and management) involves four stages: First, a feasibility study of PCM is carried out in a solar air-conditioning system. Second, a large number of studies were carried out to find a suitable PCM and its heat transfer mechanism. Scholars have sought to find suitable PCMs with the goal of improving thermal conductivity and proposed improvement methods. The research field has gradually expanded to material and geometry configuration optimization of PCM containers. Third, the energy saving and cost of PCM unit are considered for a solar air-conditioning system compared with a sensible unit. Some new system structures have been proposed to save cost and power. However, up to now, the current stage has not systematically studied the cost and operation problems caused by introducing enhanced measures to LTESs. Fourth, studies are conducted on the integration of latent thermal storage units with some components in solar air-conditioning systems such as collectors, photovoltaics, or condensers. These stages do not stagnate with each other but develop together. However, many key issues still need further discussion.

5.1 Hybrid strengthening of PCM and its container

In Chapters 2 and 3, the enhancement strategies for PCM and its containers are introduced. Some of the findings are summarized here. First, many PCMs are available in the temperature range of heat recovery, thermal power, and cold storage of SACSs. Studies concluded that the PCMs used in SACSs are mainly concentrated in paraffin, $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$, and other commercial materials. Many enhancements are also based on such materials. More suitable PCMs and strengthening methods are still waiting to be explored. In addition, the strengthening strategies mainly focused on improving the heat transfer mechanism of PCM in the container, such as to strengthen the heat conductivity of the PCM itself and to enhance the convective heat transfer in the container in the late melting stage. From the literature review, it can be concluded that the most effective way to improve the heat conductivity of PCM is by adding micro-nano additives (carbon nanotubes [73], and carbon fibers [89]) and graphite additives (expanded graphite [72]). Regarding the shape of containers, conical and wedge-shaped containers have been developed to enhance the convective heat transfer in the late stage of melting. In the geometric optimization of containers, the following methods such as increasing the specific surface area of a spherical capsule to enhance heat conduction, adjusting the ratio of upper and lower sides of wedge unit, and the eccentricity of ring are used to enhance the heat transfer effect by allowing more liquid phase of PCM to be located in the area where natural convection can occur. The

shell-and-tube design is mostly used in the structure of containers. The structures that can enhance the heat transfer area such as the serpentine tube was also used in recent systematic studies [203]. Among all the studies on strengthening strategies, the study on increasing fins is the most because of its high cost performance (easy to manufacture and low cost).

In addition, the enhancement of PCM has reached the stage of hybrid enhancement compared to single enhancement in the past. The strengthening of organic materials mainly focused on solving the comprehensive problem of poor thermal stability, flammability, and thermal conductivity. By combining metal foam and nanoparticles, a combination of graphite and nanoparticles doubled the thermal conductivity. The strengthening of inorganic materials mainly focused on solving the problems of supercooling and heat conduction, which are strengthened by a combination of nucleating agents/thickeners, nanoparticles, and metal foams. Notably, some methods have solved the problems of supercooling, phase separation, etc., but they have caused changes in thermal characteristics. For example, the addition of bentonite in $\text{CH}_3\text{COONa}\cdot 3\text{H}_2\text{O}$ has led to a decrease in latent heat [77]. At the same time, the combination of various strengthening methods has resulted in more complex changes in the thermal characteristics of PCM. For example, a low-porosity metal foam is more beneficial for increasing the heat storage time [92]. However, when nanoparticles and metal foams are used in combination to strengthen a PCM, the addition of nanoparticles reduces the effect of natural convection during PCM melting. A high-porosity metal foam is selected to ensure that the PCM volume is minimized to promote the positive contribution of natural convection [92]. Therefore, when selecting a strengthening method for PCM, the thermal conductivity and heat storage time should be balanced according to the application conditions to correctly select the amount of additive.

In addition to hybrid strengthening for PCM defects, hybrid strengthening measures for PCM and PCM containers have also been studied to increase the thermal storage efficiency of PCM unit. In the field of LTESs of SACSs, this type of hybrid strengthening studies mainly uses the method of adding nanoparticles to PCM and changing the geometric parameters of fins in the container. A series of studies [173, 185, 225] have been conducted to investigate the effect of adding different concentrations of Al_2O_3 nanoparticles and changing the size and quantity of fins. According to the analysis of melting process of PCM R82 in a triplex-tube heat exchanger, the melting time of fin group, nanoparticle group, and fin + nanoparticle group saved 59%, 17%, and 44% at the most compared to the nonenhanced group. During the solidification, the solidification time of fin group, nanoparticle group, and fin + nanoparticle group saved 55%, 8%, and 30% at the most. Notably, although the number of improvement methods has increased, the best thermal storage effect has not been achieved. Second, structural strengthening will provide better thermal storage performance improvement than PCM additives. From the perspective of heat transfer mechanism, both fin and nanoparticles can provide advantages in heat conduction in the early stage of melting, but fins can also enhance the convection in liquid PCM. In the late stage of melting, the existence of fins will suppress the buoyancy effect and thus weaken the convective heat transfer. The convection of liquid PCM is also

limited by the viscosity of nanoparticles. Eventually, the hybrid strengthening effect of nanoparticles and fins is weaker than that of individual fins. Therefore, it would be biased to consider only the advantages of increasing conduction or convection in the future studies of hybrid strengthening. Instead, the strengthening methods should be selected reasonably, and the ratios and parameters used in the methods should be adjusted to balance the benefits of heat conduction and heat convection during phase change. This will help researchers to achieve an effective hybrid improvement scheme. At the same time, hybrid strengthening methods that can be applied to the field of LTESs in SACSs have not been fully studied. For example, it is not clear whether a single high-performance additive (such as carbon nanotubes and carbon nanofibers) or a special structure (such as the PCM slabs and cascaded PCMs) can achieve better heat storage performance than a combination of traditional and cheaper strengthening methods.

5.2 Design and economic evaluation of LTESs in SACSs

From the discussion in Sections 2.3 and 5.1, we can extend a problem worthy of discussion. A simple optimization of PCM materials and containers can solve the problem of local heat conductivity, but it often causes larger problems in the system, such as cost control. For example, increasing the number of fins will reduce the PCM volume. Therefore, to satisfy the energy storage capacity of the system, it is necessary to increase the size of the system; thus, the initial investment cost and space naturally increases accordingly. However, the use of fins can significantly increase the heat storage efficiency of the system, saving electricity during the operation period. At this time, it is more important to measure the economic impact of adding a technology on the system than to measure the heat conductivity of PCM on the successful application of technology. In the LTESs, the following costs should be considered: PCM costs, container costs, enhanced technology costs, auxiliary electricity costs during operation, and other ancillary costs. The importance of these cost assessments lies in measuring the cost and benefit of design factors such as adding improvement strategies, changing operation methods, and updating system structure. On the other hand, it is expected that cost control will bring limitations and optimization to design. According to the literature review, most studies related to strengthening technology and container optimization only discussed the effect of improving system efficiency, and fewer studies theoretically calculated the economic impact of the optimal scheme on the overall system. Economic research on the application of LTESs in SACSs is also rare. We can learn the economic evaluation methods from studies of LTES in the field of solar energy application to generate positive thinking on the cost analysis of LTES in SACS. Table 11 shows the economic evaluation methods for LTES of solar thermal utilization. As shown in Table 11, for solar power systems, levelized cost of energy (LOCE) is the main economic analysis method. For small solar thermal utilization systems, such as HVAC systems and solar still systems, the main economic analysis methods are payback period and cost calculation. The separate use of these methods enables comparison of system cost under different design parameters of the LTES. Thus, the design parameters with the best economy can be obtained. But the optimal system is expected to be both energy efficient and economical. Therefore, exergy economic analysis, payback period and cost calculation can be combined in the economic analysis of the LTESs in SACSs. Limited exergy efficiency and cost can help to determine the upper and lower limits of the design parameters, and payback

period can help to determine the optimal value of the design parameters. This is more beneficial for determining the specific range of feasible design parameters. At the same time, the ratio of operating energy saving benefits to the initial investment costs of strengthening technology applied to LTESs in SACS can be considered as a simple evaluation index, which will be beneficial for the economic selection of strengthening technology.

Place Table 11 here

6. Conclusions and suggestions for future research

Latent thermal storage technology can effectively enhance the stability of solar air-conditioning systems and compensate possible power interruptions. In this paper, PCM selection methods, thermal storage container design, and the use of LTESs in SACSs are reviewed. First, this paper summarizes the available PCMs with a suitable phase transition temperature in the field of SACSs and introduces the database and evaluation methods commonly used in the selection of PCMs. Aiming at the disadvantages of PCMs, the improved methods are summarized. Second, the effect of material and geometry of PCM container is introduced. The heat transfer enhancement methods on the container side are summarized, such as fins, capsule modifications, flow direction of working fluid, PCM layouts, and other structural optimizations. Third, this paper introduced and evaluated the application of LTESs in SACSs. Then, the hybrid enhancement methods and the cost estimation method of LTESs in SACSs are discussed. The following conclusions are drawn:

(1) Although many PCMs are available at present, only some commercial materials (paraffin R series, erythritol, etc.) are used in the research work. More new materials and their enhancement methods are worth exploring.

(2) The enhanced heat transfer strategy and configuration optimization of PCM and its container mainly involve improving the heat transfer mechanism of PCM in the container. The more effective heat transfer enhancement method on a PCM is to add micro-nano additives such as carbon nanotubes and carbon nanofibers. For a container, the fins are both economical and effective. The development of new container configurations can improve the convection in the late melting stage of PCM to strengthen the heat transfer. Therefore, in the future research of PCM container optimization, the dimensionless number related to the heat transfer mechanism can be used to establish the relationship between the structure and geometrical factors of the container to achieve the design and selection of a PCM container instead of a large number of simulation studies.

(3) The strengthening of PCM and its containers has developed from the improvement of a single factor to hybrid enhancement. However, the heat storage effect of hybrid strengthening method is not always better than that of single-factor strengthening method. When selecting a hybrid strengthening strategy, the effect of strengthening strategy on the heat transfer mechanism of PCM should be considered to adjust the proportion of the method applied.

(4) The application of LTESs in SACSs is often limited because of their low-cost

performance ratio, especially in the field of heat recovery. Moreover, there is a lack of quantitative economic analysis for solar latent thermal storage air-conditioning systems. Therefore, for the cost assessment of LTESs in SACSs, we suggest that the exergy analysis, payback period and cost calculation can be combined to analyze the economy of system. This will be more beneficial for determining the specific range of feasible design parameters. At the same time, the cost evaluation of enhanced technology is relatively lacking. We suggest that the ratio of energy saving benefits to the initial investment cost can be used as a simple evaluation index to economically select the strengthening technology, which has a high potential for research.

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Reference

- [1] Galen B. U.S. Renewables Portfolio Standards 2017 Annual Status Report. Berkeley, CA: Lawrence Berkeley National Laboratory; 2017.
- [2] Indonesia National Energy Council. New Paradigm of Indonesia Energy Policy and Planning. Jakarta; 2017.
- [3] National Development and Reform Commission. Renewable energy medium and long term development planning. Renewable energy 2007;25 (6): 1-5. (In Chinese)
- [4] Beerepoot A, Marmion M. Policies for renewable heat, an integrated approach. Paris: IEA (International Energy Agency); 2012.
- [5] Helm D. The European framework for energy and climate policies. J Energy Policy 2014;64:29–35.
- [6] Connor P. Policies to support the growth of renewable energy sources of heat. J Energy Policy 2013;59:1–2.
- [7] Mcneil MA, Letschert VE. Future air conditioning energy consumption in developing countries and what can be done about it: the potential of efficiency in the residential sector. Lawrence Berkeley National Laboratory; 2007.
- [8] National Bureau of Statistics. China Statistical Yearbook (2017), <http://www.stats.gov.cn/tjsj/ndsj/> ; 2017 [accessed 20 December 2018] (In Chinese).
- [9] Longo S, Beccali M, Cellura M, Guarino, F. Energy and environmental life-cycle impacts of solar-assisted systems: The application of the tool “ELISA”. Renewable Energy 2020; 145:29-40.
- [10] Liu YF, Zhou Y, Chen YW, Wang YY, Zhu Y. Comparison of support vector machine and copula-based nonlinear quantile regression for estimating the daily diffuse solar radiation: A case study in China. Renewable Energy 2020; 146:1101-1112.

- [11] Alla SA, Bianco V, Tagliafico LA, Scarpa F, Zhu Y. An innovative approach to local solar energy planning in Riva Trigoso, Italy. *Journal of Building Engineering* 2020; 27: 100968.
- [12] Bloss WH. *Advances in solar energy technology*. Holland: D. Reidel Pub. Co.; 1988.
- [13] Li TX. *Study on an innovative multi-effect and double-way thermochemical sorption refrigeration system*. Shanghai Jiaotong University 2009.
- [14] Leflar JA, Duff WS. Solar evacuated tube collector: absorption chiller systems simulation. Nasa Sti/recon Technical Report N 1977; 79.
- [15] Luo YJ, He ZN, Wang CG. *Solar energy utilization technology*. Beijing: Chemical Industry Press; 2005.
- [16] REN21 Community. *Renewables global status report 2018*. <http://www.ren21.net/gsr-2018/>; 2018 [accessed 25 December 2018].
- [17] Wang RZ, Zhai XQ. *Energy systems in green buildings*. Shanghai: Shanghai Jiaotong University Press; 2013.
- [18] Li D, Wu Y, Liu C, Zhang G, Arıcı M. Numerical investigation of thermal and optical performance of window units filled with nanoparticle enhanced PCM. *International Journal of Heat and Mass Transfer* 2018; 125:1321-1332.
- [19] Li D, Wu Y, Liu C, Zhang G, Arıcı M. Energy investigation of glazed windows containing Nano-PCM in different seasons. *Energy conversion and management* 2018;172:119-128.
- [20] Liu C, Bian J, Zhang G, Li D, Liu X. Influence of optical parameters on thermal and optical performance of multi-layer glazed roof filled with PCM. *Applied Thermal Engineering* 2018;134:615-625.
- [21] Zayed ME, Zhao J, Elsheikh AH, Du YP, Hammad FA, Ma L, Sadek S. Performance augmentation of flat plate solar water collector using phase change materials and nanocomposite phase change materials: A review. *Process Safety and Environmental Protection* 2019;128:135-157.
- [22] Zayed ME, Zhao J, Elsheikh AH, Hammad FA, Ma L, Du YP, Shalaby SM. Applications of cascaded phase change materials in solar water collector storage tanks: A review. *Solar Energy Materials and Solar Cells* 2019;199:24-49.
- [23] Abu-Hamdeh NH, Alnefaie KA. Assessment of thermal performance of PCM in latent heat storage system for different applications. *Solar Energy* 2019;177:317-323.
- [24] L HAS, González JE, Dukhan N. Solar air conditioning systems with PCM solar collectors. *Journal of Solar Energy Engineering* 2002;128.
- [25] Allouche Y, Varga S, Bouden C, Oliveira A C. Dynamic simulation of an integrated solar-driven ejector based air conditioning system with PCM cold storage. *Applied Energy* 2017;190:600-611.
- [26] Zhai XQ, Wang XL, Wang C, Wang RZ. Experimental investigation of a novel phase change cold storage used for a solar air-conditioning system. *Hvac & R Research* 2014;20(3):302-310.
- [27] Al-Abidi AA, Mat SB, Sopian K, Sulaiman MY, Lim CH, Th A. Review of thermal energy storage for air conditioning systems. *Renewable & Sustainable Energy Reviews* 2012;16(8):5802-5819.
- [28] Li G, Hwang Y, Radermacher R. Review of cold storage materials for air conditioning application. *International Journal of Refrigeration* 2012;35(8):2053-2077.

- [29] Zhai XQ, Wang XL, Wang T, Wang RZ. A review on phase change cold storage in air-conditioning system: Materials and applications. *Renewable & Sustainable Energy Reviews* 2013;22(8):108-120.
- [30] Pintaldi S, Perfumo C, Sethuvenkatraman S, White S, Rosengarten G. A review of thermal energy storage technologies and control approaches for solar cooling. *Renewable & Sustainable Energy Reviews* 2015;41(1):975-995.
- [31] Khan MMA, Saidur R, Al-Sulaiman FA. A review for phase-change materials (PCMs) in solar absorption refrigeration systems. *Renewable & Sustainable Energy Reviews* 2017;76:105-137.
- [32] Omara AA, Abuelnour AA. Improving the performance of air conditioning systems by using phase change materials: A review. *International Journal of Energy Research* 2019.
- [33] Agyenim F, Hewitt N. Experimental investigation and improvement in heat transfer of paraffin PCM RT58 storage system to take advantage of low peak tariff rates for heat pump applications. *International Journal of Low-Carbon Technologies* 2013; 8(4):260-270.
- [34] Ma XG, Wang YH. Research and application of latent heat storage technology. *Energy research and utilization* 1991; 6: 13-17 (In Chinese).
- [35] Lane G. Latent heat materials. Florida: CRC Press; 1983.
- [36] Brancato V, Frazzica A, Sapienza A, Freni A. Identification and characterization of promising phase change materials for solar cooling applications. *Solar Energy Materials & Solar Cells* 2017; 160:225-232.
- [37] Gil A, Oró E, Peiró G, Álvarez S, Cabeza LF. Material selection and testing for thermal energy storage in solar cooling. *Renewable Energy* 2013; 57(3):366-371.
- [38] Pollerberg C, Kauffeld M, Oezcan T, Koffler M, Hanu LG, Doetsch C. Latent Heat and Cold Storage in a Solar-Driven Steam Jet Ejector Chiller Plant. *Energy Procedia* 2012; 30(1):957-966.
- [39] Helm M, Keil C, Hiebler S, Mehling H, Schweigler C. Solar heating and cooling system with absorption chiller and low temperature latent heat storage: Energetic performance and operational experience. *International Journal of Refrigeration* 2009; 32(4):596-606.
- [40] Moreno P, Solé C, Castell A, Cabeza LF. The use of phase change materials in domestic heat pump and air-conditioning systems for short term storage: A review. *Renewable & Sustainable Energy Reviews* 2014; 39(6):1-13.
- [41] Cabeza LF, Castell A, Barreneche C, Gracia AD, Fernández AI. Materials used as PCM in thermal energy storage in buildings: A review. *Renewable & Sustainable Energy Reviews* 2011; 15(3):1675-1695.
- [42] Huang F, Yu GH. Application of Small Solar Energy Absorption Refrigeration Unit on Villa. The 2001 Annual Conference of Institute of refrigeration in Shanghai. 2001. (In Chinese)
- [43] Cheng XW, Zhai XQ. Thermal performance analysis of a cascaded cold storage unit using multiple PCMs. *Energy* 2018; 143:448-457.
- [44] Allouche Y, Varga S, Bouden C, Oliveira AC. Experimental determination of the heat transfer and cold storage characteristics of a microencapsulated phase change material in a horizontal tank. *Energy Conversion & Management* 2015; 94:275-285.
- [45] Chen X, Worall M, Omer S, Su Y, Riffat S. Experimental investigation on PCM cold storage integrated with ejector cooling system. *Applied Thermal*

- Engineering 2014; 63(1):419-427.
- [46] Helm M, Hagel K, Pfeffer W, Hiebler S, Schweigler C. Solar Heating and Cooling System with Absorption Chiller and Latent Heat Storage – A Research Project Summary. *Energy Procedia* 2014; 48:837-849.
 - [47] Schweigler C, Hiebler S, Keil C, Köbel H. Low-temperature heat storage for solar heating and cooling applications. *ASHRAE Transactions* 2007; 113:89.
 - [48] Zhang S, Wu W, Wang S. Integration highly concentrated photovoltaic module exhaust heat recovery system with adsorption air-conditioning module via phase change materials. *Energy* 2016; 118.
 - [49] Ren H, Ma Z, Lin W, Fan W, Li W. Integrating photovoltaic thermal collectors and thermal energy storage systems using phase change materials with rotary desiccant cooling systems. *Sustainable Cities & Society* 2018; 36.
 - [50] Hassan MM, Beliveau Y. Modeling of an integrated solar system. *Building & Environment* 2008; 43(5):804-810.
 - [51] Poshtiri AH, Jafari A. 24-hour cooling of a building by a PCM-integrated adsorption system. *International Journal of Refrigeration* 2017; 79.
 - [52] Charvát P, Klimeš L, Ostrý M. Numerical and experimental investigation of a PCM-based thermal storage unit for solar air systems. *Energy & Buildings* 2014; 68:488-497.
 - [53] Al-Abidi AA, Mat S, Sopian K, Sulaiman MY, Mohammad AT. Experimental study of PCM melting in triplex tube thermal energy storage for liquid desiccant air conditioning system. *Energy & Buildings* 2013; 60(6):270-279.
 - [54] Fadar AE. Novel process for performance enhancement of a solar continuous adsorption cooling system. *Energy* 2016; 114:10-23.
 - [55] Agyenim F. The use of enhanced heat transfer phase change materials (PCM) to improve the coefficient of performance (COP) of solar powered LiBr/ H₂O absorption cooling systems. *Renewable Energy* 2016; 87:229-239.
 - [56] Francis A, Eames P, Smyth M. Experimental study on the melting and solidification behaviour of a medium temperature phase change storage material (Erythritol) system augmented with fins to power a LiBr/H₂O absorption cooling system. *Renewable energy* 2011; 36: 108-117.
 - [57] Gil A, Oró E, Miró L, Peiró G, Ruiz Á, Salmerón JM, Cabeza LF. Experimental analysis of hydroquinone used as phase change material (PCM) to be applied in solar cooling refrigeration. *International Journal of Refrigeration* 2014; 39(1):95-103.
 - [58] Ashby M, Johnson K. *Materials and design: the art and science of material selection in product design*. Kidlington: Elsevier Ltd; 2002.
 - [59] Yang HT, Yang RC, Yuan XB, Peng CY. Application of Material Database in Material Selection. *Development and Application of Materials* 2004; 19(2): 40-44.
 - [60] Li X, Su H, Chen XL, Yang CF, Xie G. Present status and future of materials database. *China Metallurgy* 2007; 17(6): 4-8.
 - [61] Nazir H, Batool M, Osorio FJB, Isaza-Ruiz M, Xu XH, Vignarooban K, Phelan P, Inamuddin, Kannan AM. Recent developments in phase change materials for energy storage applications: A review. *International Journal of Heat and Mass Transfer* 2019; 129: 491-523.
 - [62] Wei GS, Wang G, Xu C, Ju X, Xing LJ, Du XZ, Yang YP. Selection principles and thermophysical properties of high temperature phase change materials for thermal energy storage: A review. *Renewable and Sustainable Energy Reviews*

- 2018; 81(2): 1771-1786.
- [63] Ashby M. Materials and the environment: eco-informed material choice. Kidlington: Elsevier Ltd; 2009.
 - [64] Socaciu L, Giurgiu O, Banyai D, Simion M. PCM Selection Using AHP Method to Maintain Thermal Comfort of the Vehicle Occupants. *Energy Procedia* 2016; 85:489-497.
 - [65] Rathod MK , Kanzaria HV . A methodological concept for phase change material selection based on multiple criteria decision analysis with and without fuzzy environment. *Materials & Design* 2011; 32(6):3578-3585.
 - [66] Loganathan A, Mani I. A fuzzy based hybrid multi criteria decision making methodology for phase change material selection in electronics cooling system. *Ain Shams Engineering Journal* 2018; 9(4): 2943-2950.
 - [67] Rastogi M, Chauhan A, Vaish R, Kishan A. Selection and performance assessment of Phase Change Materials for heating, ventilation and air-conditioning applications. *Energy Conversion & Management* 2015; 89(1):260-269.
 - [68] Xu H, Jia YS, Romagnoli A, Py X. Selection of Phase Change Material for Thermal Energy Storage in Solar Air Conditioning Systems. *Energy Procedia* 2017; 105:4281-4288.
 - [69] Yang K, Zhu N, Chang C, Wang DQ, Yang S, Ma SM. A methodological concept for phase change material selection based on multi-criteria decision making (MCDM): A case study. *Energy* 2018; 165(2): 1085-1096.
 - [70] Mettawee EBS, Assassa GMR. Thermal conductivity enhancement in a latent heat storage system. *Solar Energy* 2007; 81(7):839-845.
 - [71] Lopez J, Acem Z, Barrio EPD. KNO₃/NaNO₃–Graphite materials for thermal energy storage at high temperature: part II. Phase transition properties. *Appl Therm Eng* 2010; 30 (13):1586-1593.
 - [72] Oya T, Nomura T, Tsubota M, Okinaka N, Akiyama T. Thermal conductivity enhancement of erythritol as PCM by using graphite and nickel particles. *Applied Thermal Engineering* 2013;61(2):825-828.
 - [73] Shen S, Tan S, Wu S, Guo C, Liang J, Yang Q, Xu GY, Deng J. The effects of modified carbon nanotubes on the thermal properties of erythritol as phase change materials. *Energy conversion and management* 2018;157:41-48.
 - [74] Yang L, Zhang N, Yuan Y, Cao X, Xiang B. Thermal performance of stearic acid/carbon nanotube composite phase change materials for energy storage prepared by ball milling. *International Journal of Energy Research* 2018.
 - [75] Leong KY, Ong HC, Amer NH, Norazrina MJ, Risby MS, Ahmad KZK. An overview on current application of nanofluids in solar thermal collector and its challenges. *Renewable & Sustainable Energy Reviews* 2016; 53:1092-1105.
 - [76] Zhou H, Fang CP, Sheng HS, Mu CJ. Synergistic action of nanometer ZnO prepared by sol–gel method on halogen free flame-retarded polypropylene. *Rare Metal Mater. Eng.* 2008; 37:617-619. □In Chinese□
 - [77] Zhang P, Song L, Lu HD, Wang J, Hu Y. The thermal property and flame retardant mechanism of intumescent flame retardant paraffin system with metal. *Ind. Eng. Chem. Res.* 2010; 49:6003-6009.
 - [78] Yang Z, Yang Z, Li J, Deng Y, Liu L, Luan X, Huang K. Design of diatomite-based hydrated salt composites with low supercooling degree and enhanced heat transfer for thermal energy storage. *International Journal of Energy Research* 2019.

- [79] Cabeza LF, Svensson G, Hiebler S, Mehling H. Thermal performance of sodium acetate trihydrate thickened with different materials as phase change energy storage material. *Appl. Therm. Eng.* 2003; 23:1697-1704.
- [80] Telkes M. Thermal energy storage in salt hydrates *Sol Energy Mater* 1980; 2 (4):381-393.
- [81] Mohamed SA, Al-Sulaiman FA, Ibrahim NI, Zahir MH, Al-Ahmed A, Saidur R, Yılbaş BS, Sahin AZ. A review on current status and challenges of inorganic phase change materials for thermal energy storage systems. *Renewable & Sustainable Energy Reviews* 2017; 70: 1072-1089.
- [82] Porisini FC. Salt hydrates used for latent heat storage: Corrosion of metals and reliability of thermal performance. *Solar Energy* 1988; 41(2):193-197.
- [83] Kenisarin M, Mahkamov K. Solar energy storage using phase change materials. *Renewable and Sustainable Energy Reviews* 2007; 11:1913–65.
- [84] Sakurai K, Yoshinaga N, Yagi R, Tomimatsu N, Sano K. Effect of embedding sodium acetate trihydrate on the Ag anode in an electrical nucleation cell of a supercooled latent heat storage material. *Solar Energy* 2018;173:1306-1314.
- [85] Wang Y, Yu K, Peng H, Ling X. Preparation and thermal properties of sodium acetate trihydrate as a novel phase change material for energy storage. *Energy* 2019;167:269-274.
- [86] Liu C, Hu P, Xu Z, Ma X, Rao Z. Experimental investigation on thermal properties of sodium acetate trihydrate based phase change materials for thermal energy storage. *Thermochimica acta* 2019;674:28-35.
- [87] Zhao L, Xing Y, Liu X, Luo Y. Thermal performance of sodium acetate trihydrate based composite phase change material for thermal energy storage. *Applied Thermal Engineering* 2018;143:172-181.
- [88] Oya T, Nomura T, Okinaka N, Akiyama T. Phase change composite based on porous nickel and erythritol. *Applied Thermal Engineering* 2012; 40(40):373-377.
- [89] Zhang Q, Luo Z, Guo Q, Wu G. Preparation and thermal properties of short carbon fibers/erythritol phase change materials. *Energy conversion and management* 2017;136:220-228.
- [90] Gao L, Zhao J, An Q, Zhao D, Meng F, Liu X. Experiments on thermal performance of erythritol/expanded graphite in a direct contact thermal energy storage container. *Applied Thermal Engineering* 2017;113:858-866.
- [91] Wang J, Xie H, Guo Z, Guan L, Li Y. Improved thermal properties of paraffin wax by the addition of TiO₂ nanoparticles. *Applied Thermal Engineering* 2014; 73(2):1541-1547.
- [92] Mahdi JM, Nsofor EC. Melting enhancement in triplex-tube latent heat energy storage system using nanoparticles-metal foam combination. *Applied energy* 2017;191:22-34.
- [93] Zhang Y, Sun J, Ma G, Wang Z, Xie S, Jing Y, Jia Y. Hydrophilic expanded graphite–magnesium nitrate hexahydrate composite phase change materials: Understanding the effect of hydrophilic modification on thermophysical properties. *International Journal of Energy Research* 2019;43(3):1121-1132.
- [94] Han X, Zhang X, Hua W, Yuan W, Jia X, Wang ZF. Preparation and application of composite EG/Ba (OH) 2· 8 H₂O form-stable phase change material for solar thermal storage. *International Journal of Energy Research* 2019;43(6):2227-2240.
- [95] Xie WP, Wang N, Zhu DS, Wang XJ. Review of heat transfer enhancement of

- the PCMs. Chemical Industry and Engineering Progress 2008;27(2).
- [96] Lopez J, Acem Z, Del Barrio EP. KNO₃/NaNO₃–Graphite materials for thermal energy storage at high temperature: Part II.–Phase transition properties. Applied Thermal Engineering 2010;30(13):1586-1593.
 - [97] Sarbu I, Dorca A. Review on heat transfer analysis in thermal energy storage using latent heat storage systems and phase change materials. International Journal of Energy Research 2019;43(1): 29-64.
 - [98] Gui XH, Yuan XG, Xu WQ. Numerical Simulation of Advanced Solar Dynamic System Heat Pipe Receiver. Journal of System Simulation 2005; 17(9): 2247-2250.
 - [99] Hou XB, Yuan XG, Cui HT. The Energy Analysis in Heat Receiver Cavity. Journal of Aerospace Power 2002; 17(3): 332-335.
 - [100] Regin AF, Solanki SC, Saini JS. Heat transfer characteristics of thermal energy storage system using PCM capsules: a review. Renewable and Sustainable Energy Reviews 2008; 12:2438-2458.
 - [101] Milián YE, Gutiérrez A, Grágeda M, Ushak S. A review on encapsulation techniques for inorganic phase change materials and the influence on their thermophysical properties. Renewable & Sustainable Energy Reviews 2017; 73:983-999.
 - [102] Zhang P, Qiu ZZ, He M. Review on Microencapsulated Phase Change Materials (MPCM) Slurries: Materials, Rheological Behavior and Applications. Advanced Materials Research 2014; 953-954:1109-1112.
 - [103] Huang X, Zhu CQ, Lin YX, Fang GY. Thermal properties and applications of microencapsulated PCM for thermal energy storage: A review. Applied Thermal Engineering 2019; 147:841-855.
 - [104] Al-Maghalseh M, Mahkamov K. Methods of heat transfer intensification in PCM thermal storage systems: Review paper. Renewable and Sustainable Energy Reviews 2018; 92:62-94.
 - [105] Regin AF, Solanki SC, Saini JS. Heat transfer characteristics of thermal energy storage system using PCM capsules: A review. Renewable and Sustainable Energy Reviews 2008; 12(9):2438-2458.
 - [106] Cabeza LF, Illa J, Roca J, Badia F, Mehling H, Hiebler S, Ziegler F. Immersion corrosion tests on metal-salt hydrate pairs used for latent heat storage in the 32 to 36°C temperature range. Materials and Corrosion 2001; 52(2), 140-146.
 - [107] Farrell AJ, Norton B, Kennedy DM. Corrosive effects of salt hydrate phase change materials used with aluminium and copper. Journal of Materials Processing Technology 2006; 175(1-3):198-205.
 - [108] Moreno P, Miró L, Solé A, Barreneche C, Solé C, Martorell I, Cabeza LF. Corrosion of metal and metal alloy containers in contact with phase change materials (PCM) for potential heating and cooling applications. Applied Energy 2014; 125:238-245.
 - [109] Groll M, Brost O, Heine D. Corrosion of steels in contact with salt eutectics as latent heat storage materials: Influence of water and other impurities. Heat Recovery Systems & Chp 1990; 10(5):567-572.
 - [110] Cabeza LF, Roca J, M. Nogués MH, Hiebler S. Immersion corrosion tests on metal-salt hydrate pairs used for latent heat storage in the 48 to 58°C temperature range. Materials & Corrosion 2002; 53(12): 902-907.
 - [111] Browne MC, Boyd E, McCormack SJ. Investigation of the corrosive properties of phase change materials in contact with metals and plastic. Renewable Energy

- 2017; 108:555-568.
- [112] Lázaro A, Zalba B, Bobi M, Castellón C, Cabeza LF. Experimental study on phase change materials and plastics compatibility. *Environmental and Energy Engineering* 2005; 52(2):804-808.
 - [113] Lane GA. *Solar Heat Storage: Latent Heat Materials*. Florida: CRC Press; 1986.
 - [114] Panchabikesan K, Raj AA, Ding Y, Ramalingam V. Enhancement in free cooling potential through pcm based storage system integrated with direct evaporative cooling (dec) unit. *Energy* 2017; 144:443-455.
 - [115] Su W, Darkwa J, Kokogiannakis G. Development of microencapsulated phase change material for solar thermal energy storage. *Applied Thermal Engineering* 2016; 112:1205-1212.
 - [116] Konuklu Y, Paksoy HO, Unal M, Konuklu S. Microencapsulation of a fatty acid with poly(melamine–urea–formaldehyde). *Energy Conversion and Management* 2014; 80:382-390.
 - [117] Jin Z, Wang Y, Liu J, Yang Z. Synthesis and properties of paraffin capsules as phase change materials. *Polymer* 2008; 49(12):2903-2910.
 - [118] Felipe Rodríguez, Betty LLópez. Phenolic resin/PEO-PPO block copolymer composite materials as phase change materials (PCM) for latent heat thermal energy storage (LHTES). *The Journal of Energy Storage* 2016; 6:173-177.
 - [119] Sarı A, Alkan C, Döğüşcü Derya Kahraman, Kızıl Çınar. Micro/nano encapsulated n-tetracosane and n-octadecane eutectic mixture with polystyrene shell for low-temperature latent heat thermal energy storage applications. *Solar Energy* 2015; 115:195-203.
 - [120] Hawlader MNA, Uddin MS, Khin MM. Microencapsulated PCM thermal-energy storage system. *Applied Energy* 2003; 74(1-2):195-202.
 - [121] He F, Wang X, Wu D. Phase-change characteristics and thermal performance of form-stable n-alkanes/silica composite phase change materials fabricated by sodium silicate precursor. *Renewable Energy* 2015; 74:689-698.
 - [122] Yu S, Wang X, Wu D. Microencapsulation of n-octadecane phase change material with calcium carbonate shell for enhancement of thermal conductivity and serving durability: Synthesis, microstructure, and performance evaluation. *Applied Energy*, 2014; 114(2):632-643.
 - [123] Jacob R, Bruno F. Review on shell materials used in the encapsulation of phase change materials for high temperature thermal energy storage. *Renewable and Sustainable Energy Reviews* 2015; 48:79-87.
 - [124] Fang G, Chen Z, Li H. Synthesis and properties of microencapsulated paraffin composites with SiO₂ shell as thermal energy storage materials. *Chemical Engineering Journal* 2010; 163(1-2):154-159.
 - [125] Peng K, Fu L, Li X, Ouyang J, Yang H. Stearic acid modified montmorillonite as emerging microcapsules for thermal energy storage. *Applied Clay Science* 2017; 138: 100-106.
 - [126] Zhao L, Wang H, Luo J, Liu Y, Song G, Tang G. Fabrication and properties of microencapsulated n-octadecane with tio₂ shell as thermal energy storage materials. *Solar Energy* 2016; 127: 28-35.
 - [127] Li CE, He GX, Yan HG, Yu H, Song Y. Synthesis of microencapsulated stearic acid with amorphous TiO₂ as shape-stabilized PCMs for thermal energy storage. *Energy Procedia* 2018; 152:390-394.
 - [128] Li F, Wang X, Wu D. Fabrication of multifunctional microcapsules containing n-eicosane core and zinc oxide shell for low-temperature energy storage,

- photocatalysis, and antibiosis. *Energy Conversion and Management* 2015; 106:873-885.
- [129] Li M, Liu J, Shi J. Synthesis and properties of phase change microcapsule with SiO₂-TiO₂ hybrid shell. *Solar Energy* 2018; 167:158-164.
 - [130] Dhaidan NS, Khodadadi JM. Melting and convection of phase change materials in different shape containers: A review. *Renewable and Sustainable Energy Reviews* 2015; 43:449-477.
 - [131] Arunachalam S. Latent Heat Storage: Container Geometry, Enhancement Techniques, and Applications—A Review. *Journal of Solar Energy Engineering* 2019;141(5):050801.
 - [132] Zhou J, Chen Z, Liu D, Li J. Experimental study on melting in a rectangular enclosure heated below with discrete heat sources. *Journal of Thermal Science* 2001; 10(3): 254-259.
 - [133] Shokouhmand H, Kamkari B. Experimental investigation on melting heat transfer characteristics of lauric acid in a rectangular thermal storage unit. *Experimental Thermal and Fluid Science* 2013; 50:201-212.
 - [134] Jones BJ, Sun D, Krishnan S, Garimella SV. Experimental and numerical study of melting in a cylinder. *International Journal of Heat & Mass Transfer* 2006; 49(15): 2724-2738.
 - [135] Mithat A, Orhan A, Kaygusuz K. Thermal energy storage performance of paraffin in a novel tube-in-shell system. *Applied Thermal Engineering* 2008; 28(5):405-413.
 - [136] Darzi AAR, Farhadi M, Sedighi K. Numerical study of melting inside concentric and eccentric horizontal annulus. *Applied Mathematical Modelling* 2012; 36(9):4080-4086.
 - [137] Zivkovic B, Fujii I. Analysis of isothermal phase change of phase change material within rectangular and cylindrical containers. *Solar Energy* 2001; 70(1):51-61.
 - [138] Hu ZP, Li AG, Gao R. A comparison study on the thermal performance between rectangular and wedge-shaped thermal storage units. *Journal of Xi'an University of Architecture & Technology* 2019;51(1) (In Chinese).
 - [139] Hou PM, Mao JF, Liu RR, Chen F. Design and operating characteristics of heat storage device for annular unit. *Journal of Refrigeration* 2018; 39(1):98-107 (In Chinese).
 - [140] Seddegh S, Tehrani SSM, Wang X, Cao F, Taylor RA. Comparison of heat transfer between cylindrical and conical vertical shell-and-tube latent heat thermal energy storage systems. *Applied Thermal Engineering* 2018;130:1349-1362.
 - [141] Hu ZP, Sun ZG, Li AG. Numerical Investigation of Melting Heat Transfer Enhancement of Enclosure Geometry. *Journal of Engineering Thermophysics* 2018;39(7) (In Chinese).
 - [142] Hu Z, Li A, Gao R, Yin H. Effect of the length ratio on thermal energy storage in wedge-shaped enclosures. *Journal of Thermal Analysis and Calorimetry* 2014;117(2):807-816.
 - [143] Liu FH, Wang SB, Wang H, Wang HT, Yang PY, Xiong L. Theoretical cylindrical phase change thermal storage unit performance and numerical study. *Acta Energiæ Solaris Sinica* 2015;36(3) (In Chinese).
 - [144] Wang S, Faghri A, Bergman TL. Melting in cylindrical enclosures: numerical modeling and heat transfer correlations. *Numerical Heat Transfer, Part A:*

- Applications 2012;61(11):837-859.
- [145] Dhaidan NS, Khodadadi JM, Al-Hattab TA, Al-Mashat SM. Experimental and numerical investigation of melting of nepcm inside an annular container under a constant heat flux including the effect of eccentricity. *International Journal of Heat and Mass Transfer* 2013; 67: 455-468.
 - [146] Dhaidan NS, Khodadadi JM, Al-Hattab TA, Al-Mashat SM. Experimental and numerical investigation of melting of nepcm inside an annular container under a constant heat flux including the effect of eccentricity. *International Journal of Heat and Mass Transfer* 2013; 67:455-468.
 - [147] Dutta R, Atta A, Dutta TK. Experimental and numerical study of heat transfer in horizontal concentric annulus containing phase change material. *The Canadian Journal of Chemical Engineering* 2008;86(4):700-710.
 - [148] Hu CY, Yuan YP, Cao XL, Zhang N, Yu NY. Heat transfer performance of lauric acid in eccentric unit. *Acta Energiae Solaris Sinica* 2016; 36(8):2008-2015 (In Chinese).
 - [149] Chen WZ, Cheng SM, Luo Z, Gu WM. Analysis of contact melting of phase change materials inside a heated rectangular capsule. *International journal of energy research* 1995;19(4):337-345.
 - [150] Saitoh TS, Hoshina H, Yamada K. Theoretical analysis and experiment on combined close-contact and natural convection melting in thermal energy storage spherical capsule. *Energy Conversion Engineering Conference. IEEE* 1997.
 - [151] Wei J, Kawaguchi Y, Hirano S, Takeuchi H. Study on a pcm heat storage system for rapid heat supply. *Applied Thermal Engineering* 2005; 25(17): 2903-2920.
 - [152] Salunkhe PB, Shembekar PS. A review on effect of phase change material encapsulation on the thermal performance of a system. *Renewable & Sustainable Energy Reviews* 2012; 16(8):5603-5616.
 - [153] Yamagishi Y, Sugeno T, Ishige T, Takeuchi H, Pyatenko AT. An evaluation of microencapsulated PCM for use in cold energy transportation medium. *Energy Conversion Engineering Conference. IEEE*; 2002.
 - [154] Regin AF, Solanki SC, Saini JS. Latent heat thermal energy storage using cylindrical capsule: numerical and experimental investigations. *Renewable Energy* 2006;31(13):2025-2041.
 - [155] Alvarado JL, Marsh C, Sohn C, Phetteplace G, Newell T. Thermal performance of microencapsulated phase change material slurry in turbulent flow under constant heat flux. *International Journal of Heat and Mass Transfer* 2007; 50(9-10): 1938-1952.
 - [156] Chen L, Wang T, Zhao Y, Zhang XR. Characterization of thermal and hydrodynamic properties for microencapsulated phase change slurry (mpcs). *Energy Conversion & Management* 2014; 79(79): 317-333.
 - [157] Safari A, Saidur R, Sulaiman FA, Xu Y, Dong J. A review on supercooling of phase change materials in thermal energy storage systems. *Renewable and Sustainable Energy Reviews* 2017; 70: 905-919.
 - [158] Małgorzata Jurkowska, Ireneusz Szczygiał. Review on properties of microencapsulated phase change materials slurries (mPCMS). *Applied Thermal Engineering* 2016; 98(98):365-373.
 - [159] Noro M, Lazzarin RM, Busato F. Solar cooling and heating plants: an energy and economic analysis of liquid sensible vs phase change material (pcm) heat

- storage. *International Journal of Refrigeration* 2014; 39:104-116.
- [160] Pintaldi S, Sethuvenkatraman S, White S, Rosengarten G. (2017). Energetic evaluation of thermal energy storage options for high efficiency solar cooling systems. *Applied Energy* 2017; 188: 160-177..
 - [161] Wang XL, Zhai XQ, Wang T, Wang HX. Theroetical and experimental study on solar air conditioning system with phase change cold storage. *Journal of Refrigeration* 2013; 34(5):34-40. (In Chinese)
 - [162] Najafian A, Haghighat F, Moreau A. (2015). Integration of pcm in domestic hot water tanks: optimization for shifting peak demand. *Energy and Buildings* 2015; 106: 59-64.
 - [163] Padovan R, Manzan M. Genetic optimization of a pcm enhanced storage tank for solar domestic hot water systems. *Solar Energy* 2014;103: 563-573.
 - [164] Mazhar AR, Liu SL, Shukla A. An optimizer using the PSO algorithm to determine thermal parameters of PCM: A case study of grey water heat harnessing. *International Journal of Heat and Mass Transfer* 2019; 144:118574.
 - [165] Seddegh S, Wang X, Henderson AD. A comparative study of thermal behaviour of a horizontal and vertical shell-and-tube energy storage using phase change materials. *Applied Thermal Engineering* 2016; 93:348-358.
 - [166] Mosaffa AH, Talati F, Tabrizi HB, Rosen MA. Analytical modeling of PCM solidification in a shell and tube finned thermal storage for air conditioning systems. *Energy & Buildings* 2012; 49(2):356-361.
 - [167] Khan Z, Khan Z, Tabeshf K. Parametric investigations to enhance thermal performance of paraffin through a novel geometrical configuration of shell and tube latent thermal storage system. *Energy Conversion & Management* 2016; 127:355-365.
 - [168] Erek A, Iken Z, Acar MA. Experimental and numerical investigation of thermal energy storage with a finned tube. *International Journal of Energy Research* 2005; 29(4):283-301.
 - [169] Gu YJ, Zhang C, Geng Z, Wang M. Structure optimization and heat transfer research for new type casing phase change heat sequencer. *Thermal Power Generation* 2018; (1):33-37. (In Chinese)
 - [170] Wang P, Yao H, Lan Z, Peng Z, Huang Y, Ding Y. Numerical investigation of PCM melting process in sleeve tube with internal fins. *Energy Conversion & Management* 2016; 110(FEB):428-435.
 - [171] Esapour M, Hosseini MJ, Ranjbar AA, Pahamli Y, Bahrampoury R. Phase change in multi-tube heat exchangers. *Renewable Energy* 2016; 85:1017-1025.
 - [172] Al-Abidi AA, Mat S, Sopian K, Sulaiman MY, Mohammad AT. Internal and external fin heat transfer enhancement technique for latent heat thermal energy storage in triplex tube heat exchangers. *Applied Thermal Engineering* 2013; 53(1):147-156.
 - [173] Al-Abidi AA, Mat S, Sopian K, Sulaiman MY, Mohammad AT. Numerical study of PCM solidification in a triplex tube heat exchanger with internal and external fins. *International Journal of Heat and Mass Transfer* 2013; 61(1): 684-695.
 - [174] Wu XH, Wang LX, Li WP, Zhang Lu YL. Investigation of enhanced heat transfer for triple-sleeve thermal energy storage exchangers using phase change materials. *Journal of Thermal Science and Technology* 2015; 14(2):101-105. (In Chinese)
 - [175] Liu C, Groulx D. Experimental study of the phase change heat transfer inside a

- horizontal cylindrical latent heat energy storage system. *International Journal of Thermal Sciences* 2014; 82(1):100-110.
- [176] Prieto MM, Suárez I, González B. Analysis of the thermal performance of flat plate PCM heat exchangers for heating systems. *Applied Thermal Engineering* 2017; 116:11-23.
- [177] Diarce G, Campos–Celador Á, Sala JM, García–Romero A. A novel correlation for the direct determination of the discharging time of plate-based latent heat thermal energy storage systems. *Applied Thermal Engineering* 2018;129:521-534.
- [178] Yang L, Peng H, Ling X, Dong H. Numerical analysis on performance of naphthalene phase change thermal storage system in aluminum plate-fin unit. *Heat & Mass Transfer* 2015; 51(2):195-207.
- [179] Al-Shannaq R, Kurdi J, Al-Muhtaseb S, Farid M. Innovative method of metal coating of microcapsules containing phase change materials. *Solar Energy* 2016; 129: 54-64.
- [180] Wang X, Guo Q, Wang J, Zhong Y, Wang L, Wei X, Liu L. Thermal conductivity enhancement of form-stable phase-change composites by milling of expanded graphite, micro-capsules and polyethylene. *Renewable Energy* 2013; 60: 506-509.
- [181] Wang W, Wang C, Wang T, Li W, Chen L, Zou R, Zheng J, Li XG. Enhancing the thermal conductivity of n-eicosane/silica phase change materials by reduced graphene oxide. *Materials Chemistry and Physics* 2014; 147(3): 701-706.
- [182] Li JH, Ji W, Li QB. Preparation and thermal properties of phase-change microencapsules incorporated with CNTs in the shell. *Journal of Functional Materials* 2014; 45(S2):110-114.
- [183] Yang L, Zhang X, Xu G. Thermal performance of a solar storage packed bed using spherical capsules filled with PCM having different melting points. *Energy & Buildings* 2014; 68:639-646.
- [184] Hu WJ, Chang MN, Gao Y, Zhang QL, Yang LY, Li DY. Experimental study on the cooling charge and discharge characteristics of a PCM based fin-tube thermal energy storage exchanger. *Procedia Engineering* 2017; 205:3088-3095.
- [185] Mahdia JM, Nsofor EC. Solidification enhancement of PCM in a triplex-tube thermal energy storage system with nanoparticles and fins. *Applied Energy* 2018; 211: 975–986.
- [186] Al-Abidi AA, Mat S, Sopian K, Sulaiman MY, Mohammad AT. Experimental study of melting and solidification of PCM in a triplex tube heat exchanger with fins. *Energy and Buildings* 2014; 68:33-41.
- [187] Yang X, Lu Z, Bai Q, Zhang Q, Jin L, Yan J. Thermal performance of a shell-and-tube latent heat thermal energy storage unit: role of annular fins. *Applied Energy* 2017;202: 558-570.
- [188] Campos-Celador A, Diarce G, González-Pino I, Sala JM. Development and comparative analysis of the modeling of an innovative finned-plate latent heat thermal energy storage system. *Energy* 2013; 58: 438-447.
- [189] Agyenim F, Eames P, Smyth M. A comparison of heat transfer enhancement in a medium temperature thermal energy storage heat exchanger using fins. *Solar Energy* 2009;83(9):1509-1520.
- [190] Zhai XQ, Cheng XW, Wang C, Wang RZ. Experimental investigation and performance analysis of a fin tube phase change cold storage unit for high temperature cooling application. *Energy and Buildings* 2015; 89: 9-17.

- [191] Ismail AR , Alves CLF , Modesto MS . Numerical and experimental study on the solidification of PCM around a vertical axially finned isothermal cylinder. *Applied Thermal Engineering* 2001; 21(1):53-77.
- [192] Abdulateef AM, Mat S, Abdulateef J, Sopian K, Al-Abidi AA. Geometric and design parameters of fins employed for enhancing thermal energy storage systems: a review. *Renewable and Sustainable Energy Reviews* 2018; 82:1620-1635.
- [193] Belusko M, Tay NHS, Liu M, Bruno F. Effective tube-in-tank pcm thermal storage for csp applications, part 1: impact of tube configuration on discharging effectiveness. *Solar Energy* 2015; S0038092X15005289.
- [194] Mehdi E, Arash H, Ali RDA, Mahmoud J. Melting and solidification of pcm embedded in porous metal foam in horizontal multi-tube heat storage system. *Energy Conversion and Management* 2018; 171: 398-410.
- [195] Pourakabar A, Darzi AAR. Enhancement of phase change rate of PCM in cylindrical thermal energy storage. *Applied Thermal Engineering* 2019; 150:132-142.
- [196] Lafri D, Semmar D, Hamid A, Ouzzane M. Experimental investigation on combined sensible and latent heat storage in two different configurations of tank filled with PCM. *Applied Thermal Engineering* 2019; 149:625-632.
- [197] Roberts NS, Al-Shannaq R, Kurdi J, A. Al-Muhtaseb S, Farid MM. Efficacy of using slurry of metal-coated microencapsulated PCM for cooling in a micro-channel heat exchanger. *Applied Thermal Engineering* 2017;122:11-18.
- [198] Liu C, Rao Z, Li Y. Composites Enhance Heat Transfer in Paraffin/Melamine Resin Microencapsulated Phase Change Materials. *Energy Technology* 2016; 4(4):496-501.
- [199] Li M, Wu Z, Tan J. Properties of form-stable paraffin/silicon dioxide/expanded graphite phase change composites prepared by sol–gel method. *Applied Energy* 2012; 92:456-461.
- [200] Lin Y, Zhu C, Fang G. Synthesis and properties of microencapsulated stearic acid/silica composites with graphene oxide for improving thermal conductivity as novel solar thermal storage materials. *Solar Energy Materials and Solar Cells* 2019; 189:197-205.
- [201] Yuan KJ, Wang HC, Liu J, Fang XM, Zhang ZG. Novel slurry containing graphene oxide-grafted microencapsulated phase change material with enhanced thermo-physical properties and photo-thermal performance. *Solar Energy Materials and Solar Cells* 2016; 143:29-37.
- [202] Poshtiri AH, Jafari A. 24-hour cooling of a building by a PCM-integrated adsorption system. *International Journal of Refrigeration* 2017; 79.
- [203] Kabeel AE. Solar energy assisted desiccant air conditioning system with PCM as a thermal storage medium. *Renewable Energy* 2018; 122:632-642.
- [204] Ren H, Ma Z, Lin W, Fan W, Li W. Integrating photovoltaic thermal collectors and thermal energy storage systems using phase change materials with rotary desiccant cooling systems. *Sustainable Cities & Society* 2018; 36.
- [205] Arzamendia Lopez JP, Kuznik Frédéric Baillis D, Virgone J. Numerical modeling and experimental validation of a pcm to air heat exchanger. *Energy and Buildings* 2013; 64:415-422.
- [206] Mohammadreza B, Aliakbar MS, Morteza G, Behi H, Palm B. Evaluation of a novel solar driven sorption cooling/heating system integrated with PCM Storage compartment. *Energy* 2018;164:449-464.

- [207] Francis A, Eames P, Smyth M. Experimental study on the melting and solidification behaviour of a medium temperature phase change storage material (Erythritol) system augmented with fins to power a LiBr/H₂O absorption cooling system. *Renewable energy* 2011; 36: 108-117.
- [208] Fadar AE. Novel process for performance enhancement of a solar continuous adsorption cooling system. *Energy* 2016; 114:10-23.
- [209] Neyer D, Ostheimer M, Mugnier D, White S. 10 key principles for successful solar air conditioning design – a compendium of IEA SHC Task 48 experiences. *Solar Energy* 2018; 172:78-89.
- [210] Jiang ML, Wu JY, Xu YX, Wang RZ. Transient characteristics and performance analysis of a vapor compression air conditioning system with condensing heat recovery. *Energy & Buildings* 2010; 42(11):2251-2257.
- [211] Miró L, Gasia J, Cabeza L F. Thermal energy storage (TES) for industrial waste heat (IWH) recovery: A review. *Applied Energy* 2016; 179:284-301.
- [212] Cheng WL, Mei BJ, Liu YN, Huang YH, Yuan XD. A novel household refrigerator with shape-stabilized PCM (Phase Change Material) heat storage condensers: an experimental investigation. *Energy* 2011; 36 (10):5797-5804.
- [213] Gu Z, Liu H, Li Y. Thermal energy recovery of air conditioning system – heat recovery system calculation and phase change materials development. *Appl Therm Eng* 2004; 24:2511–26.
- [214] Zhang X, Yu S, Yu M, Lin Y. Experimental research on condensing heat recovery using phase change material. *Appl Therm Eng* 2011; 31:3736-3740.
- [215] Long JY. Numerical and experimental investigation for heat transfer in triplex concentric tube with phase change material for thermal energy storage. *Solar Energy* 2008; 82(11):977-985.
- [216] Zhang X, Yu S, Yu M, Lin Y. Experimental research on condensing heat recovery using phase change material. *Appl Therm Eng* 2011; 31:3736-3740.
- [217] Belmonte JF, Izquierdo-Barrientos MA, Eguía P, Molina AE, Almendros-Ibáñez JA. PCM in the heat rejection loops of absorption chillers. A feasibility study for the residential sector in Spain. *Energy & Buildings* 2014; 80:331-351.
- [218] Helm M, Hagel K, Pfeffer W, Hiebler S, Schweigler C. Solar Heating and Cooling System with Absorption Chiller and Latent Heat Storage – A Research Project Summary. *Energy Procedia* 2014; 48:837-849.
- [219] Zhang S, Wu W, Wang S. Integration highly concentrated photovoltaic module exhaust heat recovery system with adsorption air-conditioning module via phase change materials. *Energy* 2017; 118:1187-1197.
- [220] Diaconu BM. Energy analysis of a solar-assisted ejector cycle air conditioning system with low temperature thermal energy storage. *Renewable Energy* 2012; 37(1):266-276.
- [221] Chen X, Worall M, Omer S, Su Y, Riffat S. Experimental investigation on PCM cold storage integrated with ejector cooling system. *Applied Thermal Engineering* 2014; 63(1):419-427.
- [222] Zheng L, Zhang W, Xie L, Wang W, Tian H, Chen M. Experimental study on the thermal performance of solar air conditioning system with MEPCM cooling storage. *International Journal of Low-Carbon Technologies* 2019; 14(1):83-88.
- [223] Huang F, Yu GH. Application of Small Solar Energy Absorption Refrigeration Unit on Villa. The 2001 Annual Conference of Institute of refrigeration in Shanghai. 2001. (In Chinese)

- [224] Allouche Y, Varga S, Bouden C, Oliveira AC. Experimental determination of the heat transfer and cold storage characteristics of a microencapsulated phase change material in a horizontal tank. *Energy Conversion & Management* 2015; 94:275-285.
- [225] Mahdi JM., Lohrasbi S, Ganji DD, Nsofor EC. Accelerated melting of PCM in energy storage systems via novel configuration of fins in the triplex-tube heat exchanger. *International Journal of Heat and Mass Transfer* 2018;124:663-676.
- [226] Godarzi AA, Jalilian M, Samimi J, Jokar A, Vesaghi MA. Design of a PCM storage system for a solar absorption chiller based on exergoeconomic analysis and genetic algorithm. *International journal of refrigeration* 2013;36(1):88-101.
- [227] Noro M, Lazzarin RM, Busato F. Solar cooling and heating plants: An energy and economic analysis of liquid sensible vs phase change material (PCM) heat storage. *International journal of refrigeration* 2014;39:104-116.
- [228] Ghorbani B, Mehrpooya M, Sharifzadeh MMM. Introducing a hybrid photovoltaic-thermal collector, ejector refrigeration cycle and phase change material storage energy system (Energy, exergy and economic analysis). *International Journal of Refrigeration* 2019;103:61-76.
- [229] Kabeel AE, Abdelaziz GB, El-Said EMS. Experimental investigation of a solar still with composite material heat storage: Energy, exergy and economic analysis. *Journal of Cleaner Production* 2019;231:21-34.
- [230] Bai F, Wang Y, Wang Z, Sun Y, Beath A. Economic evaluation of shell-and-tube latent heat thermal energy storage for concentrating solar power applications. *Energy Procedia* 2015;69:737-747.
- [231] Thaker S, Oni AO, Kumar A. Techno-economic evaluation of solar-based thermal energy storage systems. *Energy Conversion and Management* 2017;153:423-434.
- [232] Nithyanandam K, Pitchumani R. Cost and performance analysis of concentrating solar power systems with integrated latent thermal energy storage. *Energy* 2014;64:793-810.

Tables

Table 1

The characteristics of different types of PCMs

| Properties | Organic | Inorganic | Eutectic |
|--------------------------------|-------------|---|--|
| Phase change enthalpy per unit | Low | Higher than organic PCMs | The higher the proportion of high melting entropy components, the higher the Phase change enthalpy of eutectic PCMs. |
| Supercooling | Low or no | Yes | Yes |
| Toxic | No | Low or no | Low or no |
| Corrosives | No | Yes | Yes |
| Cost | Low | The cost of salt hydrates is low; the costs of molten salts and metallic alloys are higher than organic PCMs. | The cost of eutectic PCM is related to its composition. |
| Application in LTESs of SACSs | Widely used | Extensively used | Frequently used in cold storage applications |

Table 2

Ideal properties of PCMs applied in solar air conditioning system

| Classifications | Properties | Measure Indexes |
|---------------------|--|--|
| Thermal Properties | Phase change temperature matched with heat and cold storage conditions | Melting temperature/ Solidification temperature [$^{\circ}\text{C}$] |
| | High latent heat | Enthalpy of fusion/ solidification [kJ/kg] |
| | Excellent thermal conductivity | Thermal conductivity [$\text{W}/(\text{m}\cdot\text{K})$] |
| Physical Properties | High density | Density [kg/m^3] |
| | High specific heat capacity | Specific heat capacity [$\text{kJ}/(\text{kg}\cdot\text{K})$] |
| | Small change of volume in phase transition | Volume expansion rate [%] |
| | Minimum super-cooling | Degree of super-cooling [$^{\circ}\text{C}$] |
| Chemical Properties | Non-toxic | |
| | Non-corrosiveness | |
| | Long-term stability of chemical properties | |
| Economics | Low-cost | |
| | Abundant resource | |

Table 3

The appropriate melting temperature range in the application field of different solar energy storage

| Application | The melting temperature range of PCMs °C | References |
|--|---|------------|
| Heat storage in SACSs | Above 25 | [29] |
| Solar energy absorption (single effect) system | 60-120 | [36] |
| Solar energy absorption (dual effect) system | 140-200 | [37] |
| Driving solar ejector cooling system | 120-150 | [38] |
| Heat recovery of solar absorption cooling system | 25-30 | [39] |
| Heat recovery of condenser applied in the compression system | 40-50 | [40] |
| Cold storage in SACSs | Up to 20 | [41] |
| Solar energy absorption (single effect) system applied in the field of freezing | -10-15 | [31] |
| Compression cooling system | 5-10 | [29] |

Table 4

The PCMs considered for use in the LTESS field in SACSs

| Materials | Types of materials | Melting temperature | Heat of fusion | Thermal conductivity | Specific heat capacity | Applicable scenarios in Reference | Reference |
|---|--------------------|---------------------|----------------|----------------------|------------------------|---|-----------|
| □ | □ | °C | kJ/kg | W/(m·K) | kJ/(kg·K) | □ | □ |
| Parafol 14 (tetradecane 97 %) | Organic | 4-8.0 | 220 | □ | □ | Cold storage for an ejector cooling system | [38] |
| Parafol 14/16 (13 vol.-% of Parafol 14) | Eutectic | 6-13.0 | 170 | □ | □ | Cold storage for an ejector cooling system | [38] |
| RT 10 | Organic | 8.7-11.7 | 176 | □ | □ | Cold storage for an ejector cooling system | [38] |
| Na ₂ SO ₄ ·10H ₂ O | Eutectic | 12.8 | □ | □ | □ | Cold storage for an absorption cooling system | [42] |
| Capric-Lauric acid eutectic and 10% Oleic acid | Eutectic | 13 | 90.9 | 0.207 | 2.196 | Cold storage for a solar cooling system | [43] |
| RT15 | Organic | 13.2-15.8 | 40.81 | □ | 6-20.0 | Cold storage for an ejector cooling system | [25, 44] |
| Capric-Lauric acid eutectic and 6% Oleic acid | Eutectic | 14.5 | 109.7 | 0.208 | 2.214 | Cold storage for a solar cooling system | [43] |
| Parafol 16/18 (67 vol.-% of Parafol 16) | Eutectic | 15-19.5 | 170 | □ | □ | Cold storage for an ejector cooling system | [38] |
| S15 | Inorganic | 15 | 142 | 0.43 | 0.67 | Cold storage for an ejector cooling system | [45] |
| capric and lauric acid | Eutectic | 16.91 | 115.1 | 0.572 | 1.825 | Cold storage for an adsorption cooling system | [26] |
| Capric-Lauric acid eutectic and 2% Oleic acid | Eutectic | 17 | 127.2 | 0.213 | 2.232 | Cold storage for a solar cooling system | [43] |
| RT 20 | Organic | 17.2-24.2 | 142 | □ | □ | Cold storage for an ejector cooling system | [38] |

| | | | | | | | |
|---------------------------------------|-----------|-----------|---------|-------|------|---|--------------|
| Parafol 16 (hexadecane 97 %) | Organic | 17.4-20.7 | 249 | □ | □ | Cold storage for an ejector cooling system | [38] |
| Heptadecane | Organic | 19.9-22.7 | 168 | □ | □ | Cold storage for an ejector cooling system | [38] |
| CaCl ₂ ·6H ₂ O | Inorganic | 27-29 | 150-240 | □ | □ | Heat storage in heat recovery system of an absorption cooling system | [39, 46, 47] |
| RT44 | Organic | 39.1-42.5 | 256.9 | 0.2 | 2 | Store the waste heat of the photovoltaic module to drive an adsorption air conditioning | [48] |
| RT55 | Organic | 51-57 | 170 | 0.2 | 2 | Heat storage for driving a desiccant cooling system | [49] |
| Paraffin (85.1%) | Organic | 55 | 179 | 0.2 | □ | Heat storage for driving a desiccant cooling system | [50] |
| RT60 | Organic | 55-61 | 160 | 0.2 | 2 | Heat storage for driving a desiccant cooling system | [49] |
| RT65 | Organic | 57-68 | 150 | 0.2 | 2 | Heat storage for driving a desiccant cooling system | [49] |
| Stearic acid | Organic | 69 | 202.5 | 0.172 | 2.2 | Heat storage for driving an adsorption cooling system | [51] |
| RT70HC | Organic | 69-71 | 260 | 0.2 | 2 | Heat storage for driving a desiccant cooling system | [49] |
| RT42 | Organic | 38-43 | 174 | 0.2 | 2 | Heat storage for driving a desiccant cooling system | [52] |
| RT82 | Organic | 81-85 | 176 | 0.2 | 2 | Heat storage for driving a liquid desiccant cooling system | [53] |
| S83 | Inorganic | 83 | 141 | 0.62 | 2.31 | Heat storage for driving an adsorption cooling system | [54] |
| S89 | Inorganic | 89 | 151 | 0.67 | 2.48 | Heat storage for driving an adsorption cooling system | [54] |
| RT100 | Organic | 99 | 168 | 0.2 | 2.4 | Heat storage for driving an LiBr/H ₂ O adsorption cooling system | [55] |
| MgCl ₂ ·6H ₂ O. | Inorganic | 116.7 | 168.6 | 0.7 | 2.6 | Heat storage for driving an LiBr/H ₂ O adsorption cooling system | [55] |

| | | | | | | | |
|--|----------|---------|---------|-------|------|--|------|
| Erythritol | Organic | 117.7 | 339.8 | 0.326 | 2.76 | Heat storage for driving a single effect LiBr/H ₂ O absorption cooling system | [56] |
| Polyethylene PE-HD [GHR 8110] | Organic | 122-133 | 150-200 | □ | □ | Heat storage for driving an ejector cooling system | [38] |
| Polyethylene PE-UHM [GUR4120] | Organic | 124-134 | 150-200 | □ | □ | Heat storage for driving an ejector cooling system | [38] |
| Polyethylene Licocene PE 4201 | Organic | 125-130 | 246 | □ | □ | Heat storage for driving an ejector cooling system | [38] |
| KNO ₃ -NaNO ₂ -NaNO ₃ (53-40-7) | Eutectic | 142 | 80 | □ | □ | Heat storage for driving an ejector cooling system | [38] |
| Palatinitol (Isomalt) | Organic | 145 | 170 | □ | □ | Heat storage for driving an ejector cooling system | [38] |
| Mannitol | Organic | 167 | 325 | □ | □ | Heat storage for driving an ejector cooling system | [38] |
| Hydroquinone | Organic | 172.5 | 225 | □ | □ | Heat storage for driving an adsorption cooling system | [57] |

Table 5

The defects of PCMs and corresponding solutions

| Defect of material | Approaches to strengthen the heat transfer | Details | References |
|--------------------------|---|--|------------|
| Low thermal conductivity | Adding a material with large thermal conductivity | Adding aluminum powder, expanded graphite, carbon fiber and carbon nanotubes | [70-74] |
| | Adding Nano-Particles | | [75] |
| Leakage of PCM | Encapsulation of the PCM | Encapsulating in spherical capsules or microcapsules | [28] |
| | Forming CPCMs | Metal foams, porous carbon materials, such as expanded graphite, carbon nanotubes, graphite foams. | [71] |
| High flammability | Addition of flame retardants | Forming nano-composite PCMs | [76] |
| | | Adding metals, such as iron, magnesium, aluminum, and zinc | [77] |
| Phase separation | Adding gelling or thickening agent | The addition of starch | [28] |
| | | The addition of cellulose derivatives, such as methyl cellulose and hydroxyethyl methyl cellulose | |
| | | The addition of diatomite | [78] |
| | | The addition of bentonite | [79] |
| Super-cooling | Encapsulating PCMs | | [28] |
| | Adding nucleating agents | Carbon nanofibers, copper, titanium oxide, potassium sulfate, and borax | [28] |
| | Cold finger | | [80] |

| | | | |
|-----------|--|--|------|
| Corrosive | Preparing porous surfaces | | [81] |
| | Addition of additives to improve chemical stability | Adding NaCl | [28] |
| | Selection of a container with excellent corrosion resistance | Stainless steel is more resistant to salt hydrates than carbon steel, aluminum alloy and copper. | [82] |
| | | Polypropylene and polyolefins could be used as container materials to resist most PCMs. | [83] |

Table 6

The PCM enhancement methods applied to LTESSs in SACSs.

| PCM | Additives | Control Variables | Key observation | Evaluation index | Recommended parameters | Improvement effect | Remarks | Reference |
|--------------|---|---|--|--|---|--|--|-----------|
| Paraffin wax | Aluminum | Aluminum mass fraction was 0, 0.1 wt%, 0.3wt%, 0.4wt% and 0.5wt%, respectively. | Temperature distribution; the position of the phase change interface | Charging process: the average heat transfer coefficient Discharging process: The mean daily efficiency | The recommended mass fraction of aluminum is 0.5. | The average daily heat storage efficiency of composite PCM was increased by 82%-94%. | | [70] |
| Erythritol | Spherical graphite / expanded graphite/ nickel particle | The range of each filler content was 1-44 vol %. | Thermal conductivity | Theoretical effective thermal conductivity base on the Nielsen's model | | The thermal conductivity increases with the increase of additive content. Compared with the pure PCM, the thermal conductivity of PCM with 15 vol% expanded graphite increased by 640%; the thermal conductivity of PCM with 17 vol% spherical graphite increased by 290%. | The enhancement effect of expanded graphite was greater than that of spherical graphite; the enhancement effect of nickel particles was the worst among the three. | [72] |
| Erythritol | Modified multi-walled carbon nanotubes with average diameter and length of 10 nm and 50 μm , respectively. | (1).The pretreatment methods of multi-walled carbon nanotubes are different: ball milling, mechanochemistry and acid oxidation; (2). the content of modified multi-walled carbon nanotube is 0.5, 1, 2, 3, 4 and 5 wt%, respectively. | Melting enthalpy; melting point; solidification enthalpy; solidification point | | Acid oxidation treatment is recommended. | The addition of 1% modified multi-walled carbon nanotubes increased the thermal conductivity of PCM from 0.1956 W/ (m.K) to 0.9779 W/ (m.K). | | [73] |

| | | | | | | | | |
|---|--|--|---|--|---|--|--|------|
| Paraffin wax | Iron/ magnesium/ aluminum/ zinc (75-150 μm in diameter) | The quantity of each filler content was 0%, 1%, 3%, 5% parts per hundred paraffin, respectively. | Volatilization intensity of carbon dioxide and ammonia; the maximum heat release capacity; the heat release rate; phase transition temperature; latent Heat | | | Metal (iron, magnesium, aluminum, and zinc) can enhance flame retardancy and thermal stability of the paraffin. | The latent heat of PCM decreased by about 20 kJ/kg after adding metal. | [77] |
| $\text{CH}_3\text{COO Na}\cdot 3\text{H}_2\text{O}$ | 20wt% simple wheat flour/ 30wt% methyl hydroxyethyl-cellulose/ 30wt% methyl-cellulose/ 50wt% bentonite | (1). Different kinds of thickeners: starch, cellulose and bentonite; (2). Different kinds of cellulose with the same content: 30 wt% methyl hydroxyethyl-cellulose and 30 wt% methyl-cellulose. | Melting temperature; measured enthalpy | | 30wt% methyl hydroxyethyl-cellulose and methyl-cellulose are recommended. | All three materials possess the properties of thickening, but the PCM with bentonite had a supercooling temperature of 10 $^{\circ}\text{C}$. | The addition of starch suspected to change the melting point and freezing point of PCM. | [79] |
| $\text{CH}_3\text{COO Na}\cdot 3\text{H}_2\text{O}$ | Ag anode | (1). The direct-current voltage range was 0.8-2.0 V; (2). The degrees of supercooling was 48 $^{\circ}\text{C}$, 38 $^{\circ}\text{C}$, 28 $^{\circ}\text{C}$, and 18 $^{\circ}\text{C}$, respectively; (3). Operational cycle numbers were 0, 1000, 2000, 5000, and 10,000; (4). The surface roughness of the Ag electrode was 0.05-2 μm . | Induction time of the electrical nucleation; the retention time of the supercooled solution | | (1). Voltage over 1.4-1.8 is required; (2). The optimal range of surface roughness of the Ag electrode is 0.6-1.0 μm | The electronucleation system mentioned in this paper can be supplied by 1.5V dry batteries and obtain 100% nucleation. The electronucleation method has reliability and repeatability. | (1). The experiment was carried out on a heat storage system with a 5 L PCM container at most; (2). The electronucleation system with the optimal parameters mentioned in this paper can be used for more than 10 years when only one to two operations per day are performed. | [84] |

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| CH ₃ COO Na·3H ₂ O | Nucleating agent: Na ₄ P ₂ O ₇ ·10H ₂ O ; thickening agent: polyacrylamide | (1). The content of polyacrylamide was 1.0 wt%, 1.5 wt% and 2.0 wt%, respectively; (2). The concentration range of sodium acetate was 96-98 wt%. | Supercooling degree; distinct phase stratification; melting temperature | | (1).1.5% mass ratio of the polyacrylamide is required to avoid phase stratification; (2) . CH ₃ COONa·3 H ₂ O with 1.5 wt% of Na ₄ P ₂ O ₇ ·10H ₂ O can achieve the lowest supercooling degree. | The addition of 1.5 wt% Na ₄ p ₂ o ₇ 10H ₂ O can reduce the supercooling of PCM to 4K. | [85] |
| CH ₃ COO Na·3H ₂ O | Silicon carbide and bentonite | The mass fractions of bentonite: 1-50 wt %; the mass fraction of silicon carbide: 0.5-15 wt% | The melting temperatures and peak temperatures; supercooling degree; heat storage time; heat release time | | (1). The mass fraction of bentonite over 26 wt.% is needed for infiltration avoidance; (2). When the content of silicon carbide is more than 10wt%, PCM have almost no supercooling. | The addition of silicon carbide and bentonite improves the leakage, thermal stability, supercooling and thermal conductivity of PCMs. The addition of 26 wt% bentonite and 10 wt% reduced the heat storage and release time of PCM by 25.44% and 78.5%, respectively. | The addition of bentonite and SC lead to a decrease in latent heat. [86] |
| CH ₃ COO Na·3H ₂ O | Disodium hydrogen phosphate dodecahydrate/ sodium carbonate decahydrate/ sodium silicate nonahydrate/ | The amount of each additive is 2, 4, 6, 8 wt%, respectively; the porosity of copper foam is 98%, 88%. | Subcooling degree; latent heat; phase change temperature; phase change time | Theoretical effective thermal conductivity base on the Bhattacharya model | (1).2 wt% carboxymethyl cellulose and 2 wt% disodium hydrogen phosphate dodecahydrate i | The supercooling of PCM with 2 wt% carboxymethyl cellulose and 2 wt% disodium hydrogen phosphate dodecahydrate was reduced to 4.6K. | [87] |

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| | b o r a x decahydrate/ quart sand/ the carboxymethyl cellulose/ copper foams | | | | recommended; (2). the 88% porosity of copper foam is recommended. | | | |
| Erythritol | Porous nickel | Pore sizes of 100, 300, and 500 μm | | Theoretical effective thermal conductivity | The 15 vol% porous nickel with a pore size of 500 μm is recommended. | The thermal conductivity of erythritol increased to 11.6W/ (m.K) by adding 15 vol% porous nickel with a pore diameter of 500 μm , which was two orders of magnitude higher than that of pure erythritol. | The pore size has no effect on melting point and latent heat. | [88] |
| Erythritol | Short carbon fiber with diameter of about 9 μm | (1). The aspect ratio of SCF is 5 and 25; (2). the mass fraction of 1, 2, 4, 7 and 10 wt% | Graphitization morphology; heat storage time; thermal conductivity | | The aspect ratio of 25 is recommended. | The addition of 10 wt% short carbon fiber with an aspect ratio of 25 led to an increase in the thermal conductivity of PCM by 407.8%. | T h e r m a l conductivity of PCM changes after cycling. After one cycle, the thermal conductivity of PCM with 10 wt% short carbon fiber (aspect ratio of 25) was reduced by 21.1%. | [89] |
| Erythritol | E x p a n d e d graphite | The amount of 1, 2, 3 and 4wt% | Melting time; t h e r m a l conductivity | | From the point of view of t h e r m a l conductivity, the addition of 4 wt% e x p a n d e d graphite is the b e s t . Considering the melting time, 3 wt% e x p a n d e d graphite is | The thermal conductivity of PCM with 4wt% expanded graphite increased about 2.5 times, and the composite phase change material had a 16.7% lower melting time than pure erythritol. | | [90] |

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| | | | | | recommended. | | | |
| Paraffin wax | TiO ₂ | The range of content was 0-7 wt%. | Thermal conductivity; phase transition temperature; latent heat capacity | Theoretical effective thermal conductivity | 0.7wt% TiO ₂ is recommended. | The addition of 0.7 wt% TiO ₂ improved the thermal conductivity of paraffin wax by 20.1J/g. Composite PCM has lower latent heat capacity than paraffin when the content of TiO ₂ was more than 2wt%. | | [91] |
| RT82 | Al ₂ O ₃ nanoparticles and porous copper foam | (1). The content of Al ₂ O ₃ nanoparticles is 0, 0.01, 0.03, and 0.05, respectively; (2). the porosity of copper foam is 95% and 98%. | Liquid fraction; isotherm at different melting times; melting time | | Low volume fraction of Al ₂ O ₃ nanoparticle and high porosity copper foam are recommended. | The addition of Al ₂ O ₃ nanoparticles and porous copper foam resulted in a 7-90% savings in heat storage time. | | [92] |

Table 7

The heat transfer enhancement technologies for different thermal storage containers

| The types of thermal storage container | Approaches to strengthen the heat transfer | Details | References |
|--|--|---|------------|
| Shell and tube | Changing the direction of the heat exchanger | The horizontal type has a better heat transfer performance compared to the vertical type. | [165] |
| | Changing the geometric shape of the shell | The time of the solidification of PCM is shorter in the cylindrical shell compared to the rectangular shell. | [166] |
| | The use of fin | It was observed that copper, aluminium and aluminium 6063 had considerably better thermal performance with paraffin as compared to steel AISI 4340. | [167] |
| | The change of fin materials | | |
| | The change of fin length | The melting time reduced by 57.32% as the length of the fin is increased from 12.7 mm to 38.10 mm. | [167] |
| | | The stored energy increases with increasing fin radius. | [168] |
| | The change of fin thickness | The thermal storage capacity of the system is decreased by 5.7% as the fins' thickness is increased from 1 mm | [167] |

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| | | | to 5 mm. | |
| | | The change of fin space | The stored energy increases with decreasing fin space. | [168] |
| Sleeve tube | Adjusting the arrangement of heat transfer tube bundles | | The melting time of PCM is shortest when the heat transfer tube was arranged in a concentric circle, compared with the staggered square pitch, in-line square pitch and in-line triangle pitch. | [169] |
| | The use of fin | The change of angles between neighbor fins | The angle between the neighbor full-scale fins set to 60-90°, and the thermal performance of the system is best. | [170] |
| | | The change of fin thickness | The influence of fin thickness is very small compared with that of the angle between neighbor fins. | [170] |
| | Changing the quantity of the inner tube | | The four-tube type reduced the melting time of the PCM by 29%. | [171] |
| Multi-tube | The use of fin | The position of added fins | The heat transfer capability of adding internal and external fins is stronger than that of adding internal fins and external fins respectively. | [172, 173] |
| | | The change of the geometric shape of the fin | The use of direct and T shaped fins can be used to further enhance heat transfer. | [174] |
| | | The change of the quantity of the fins | The more the fins, the shorter the melting time of PCMs. | [172, 173] |

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| | | | The change of fin length | The melting time decreased as the fin length increases. | [172, 173] |
| | | | The change of fin thickness | The influence of the fin thickness could be ignored. | [172, 173] |
| Cylindrical type | The use of fin | The change of fin angles | | When the temperature of HTF is low (50 °C), the fin with an angle can slightly shorten the melting time. But when the temperature of the HTF is high (60 °C), the influence of the angle fin could be ignored. | [175] |
| Flat plate | Changing the direction of plate | | | With the horizontal arrangement of PCM capsules arrangement, the heat transfer rates increase up to twofold. | [176] |
| | | | | The decrease of PCM thickness makes the heat transfer rate increase by five times. | [176] |
| | The change of plate thickness | | | The function correlation developed can be used for simplified design procedures to calculate the maximum plate thickness that can be used to optimize thermal performance. | [177] |
| Plate-fin | The use of fin | The change of fin length | | The impact of increasing the fin length can be ignored. | [178] |
| | | The change of fin space | | The smaller the fin space, the shorter the melting/ solidification time. | [178] |
| Capsule | Modification of Capsule Material | The addition of metal coating | | The heat transfer coefficient of mPCM slurry with metal coating can be increased by over 10%, compared | [179] |

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| | with the non-metal coating type. | |
| The addition of expanded graphite | Adding 10% expanded graphite to the shell can increase thermal conductivity of the mPCM by 10 times. | [180] |
| graphene oxide | 1 wt% of graphene dosing already results in a notable increase of the thermal conductivity. | [181] |
| nanotubes | The thermal conductivity sees a nearly double increase by adding 0.15g of nanotubes results in shell. | [182] |
| Multiple PCMs | The average energy and exergy collection efficiency of the system are increased significantly. | [183] |

Table 8

The latent application for driving solar air conditioning

| Types of solar collector | Types of system | Types of materials | Materials | Storage containers | Research method | Application evaluation | References |
|--------------------------|---------------------------------------|--------------------|--|---|---|--|------------|
| Flat plate | Adsorption | Organic | Stearic acid | Shell and tube | Theoretical simulation | Compared with the system without PCM, the use of PCM reduced the auxiliary energy consumption at night by about 31%. But even with the application of PCM, the whole system still consumed 3.28 times more energy than the ordinary split air conditioning system. | [202] |
| Air collector | Desiccant | Organic | Paraffin | Rectangular container with serpentine tube inside | Theoretical simulation | This study compared the energy-saving performance of desiccant air conditioning driven by pure electric heating (A type), electric heating + solar heating (B type), electric heating + PCM + solar heating (C type). The results show that compared to the purely electric drive type, the energy saving rate of C-type was up to 75.82% which was nearly four times that of the B type. In addition, the C-type had the highest total fixed cost, twice that of the A-type, but the total annual operating cost of C-type was 626 LE, which was about a quarter of the A-type. | [203] |
| | Desiccant | Organic | RT65 | The PCM TES unit consists of multiple PCM layers arranged in parallel | Theoretical simulation | At regenerative temperatures of 60 °C, 65 °C and 70 °C, the system could achieve a humidity satisfaction rate of over 80%. At the temperature of 60 °C, the regeneration coefficient could reach 100%. This study proved the technical feasibility of using mixed PVT-SAH and LTESS to drive the desiccant wheel regeneration. | [204] |
| Evacuated tube collector | Ejector | Organic | Polyethylene | Buffer tanks | Theoretical simulation | The PCM unit of 800 kg polyethylene could produce 62.5 kg of steam. Under rated operating conditions, the solar ejector cooling system operated at full load for more than 15 minutes. | [38] |
| | LiCl-H ₂ O sorption module | Organic | RT11(cold storage)/RT27(h eat storage) | Tubular double jacket heat exchanger | Theoretical simulation and experimental study | The results of both experiment and simulation indicated that this new solar adsorption air-conditioning system is feasible, and the average COP can reach 0.36 (cooling) and 0.42 (heating). | [206] |

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|----------------------------------|--|-----------|------------|------------------------|---------------------------|---|-------|
| | Single effect LiBr/H ₂ O absorption | Organic | Erythritol | Shell and tube | Theoretical simulation | The energy stored in a 20 kg PCM could be released by 70.9% within 200 minutes. | [207] |
| Parabolic trough collector | Adsorption | Inorganic | S89/S83 | Cylindrical storage | Theoretical simulation | LTESS could only be applied when the collector area is higher than 0.9 m ² . When LTESS was applied, the number of daily refrigeration cycles increased from 25 to 37, and the daily refrigerating capacity increased by 785 kJ/kg. The continuous cooling time was extended to 26.28 h. | [208] |

Table 9**The latent application for heat recovery**

| Types of system | Installation position | Types of materials | Materials | Storage containers | Research method | Application evaluation | References |
|---|---|--------------------|--|-----------------------|---|--|------------|
| Absorption | The PCM unit is integrated in the dry cooler | Inorganic | $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ | Capillary tubes | Experimental study | At runtime, the PCM unit stored approximately 50% of the daily waste heat under hot ambient condition (32 °C) and released heat from PCM units below 20 °C. In addition, the PCM unit has 10 times volume storage density compared to the water system, which reduces the cost and size of the entire system. | [39] |
| | The PCM unit is integrated in the dry cooler | Inorganic | Hydrated salts | Well-mixed tank | Theoretical simulation and experimental study | During the experiment, the PCM unit could store 65.22 kWh in 12 hours. The integrated system of PCM unit and dry cooler was not suitable for areas with high ambient temperature, such as Serbia. The overall efficiency of the whole system was improved by 50% and the COP increased by 1 unit, compared to the system with wet cooler. | [217] |
| | The PCM with dry re-cooled sorption chiller in the heat rejection loops | Inorganic | $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ | Capillary tubes | Experimental study | The application of PCM unit raised efficiency of the whole system up to 64% compared to a system with only dry re-cooling. | [218] |
| Absorption cooling system driven by photovoltaic waste heat | Composite phase change material (CPCM) and PCM (auxiliary) regenerative system are integrated in the heat exhaust system to recover the residual heat of photovoltaic | | CPCM: Acetamide with 20 wt% expanded graphite; PCM: RT44 | Rectangular container | Theoretical simulation | The authors designed a PCM unit to absorb the wasted heat generated by the photovoltaic module to drive an adsorption air conditioning unit or a hot water system. They presented a theoretical COP calculation method of the system. PCM unit can improve COP of whole system significantly in theory, compared to the systems without PCM units. But unfortunately, the author did not make a quantitative comparison between the two. | [219] |

Table 10**The latent application for cold storage**

| Types of system | Installation position | Types of materials | Materials | Storage containers | Research method | Application evaluation | References |
|-----------------|--|--------------------|---|---|------------------------|--|------------|
| Absorption | Connection with the refrigeration unit | Eutectic | Na ₂ SO ₄ ·10H ₂ O | Shell and tube | Theoretical study | It is feasible for the design system to store energy during the daytime and supply single effect absorption air conditioning at night. | [223] |
| Adsorption | Connection with the solar adsorption chiller | Eutectic | Capric and lauric acid | Spherical capsule packed bed | Experimental study | In the stable state, the charging and discharging period could be 230 and 220 minutes respectively. | [26] |
| Ejector | In chilled water networks | Organic | 30 wt. %paraffin/water dispersion | Buffer tank (phase change slurry) | Theoretical simulation | The PCM unit can diminish the scale of the total system and fulfill the demand for refrigeration. | [38] |
| | Between Air handler and Evaporator | Organic | RT15 | Horizontal tank with tube-bundle heat exchanger | Experimental study | The maximum COP of the ejector cooling system with PCM was 0.193, and the monthly average COP was almost no change and nearly twice that of the system without PCM unit. | [25, 224] |
| | The PCM cold storage charging unit integrates with the evaporator vessel | Inorganic | S15 | Finned straight tube PCM tank | Experimental study | The COP of injection systems cooling system without PCM unit was reduced from 0.315 to 0.216. The cop of the system with PCM unit could keep constant value of 0.31. | [222] |

Table 11

Economic evaluation for LTES of solar thermal utilization.

| System | System size | Economic evaluations | Optimized objects | Details | References |
|--|--|--|-------------------|--|------------|
| Solar absorption system with LTES | Total system load of 45.4kW | Payback period | | In this paper, solar absorption chiller without latent heat storage system is optimized by exergy economy analysis and genetic algorithms. The payback period of the optimal solar absorption chiller with the latent heat storage unit was calculated. The results show that using latent storage system was caused payback period increase from 0.61 years to 1.13 years in optimum point. | [226] |
| Solar single-stage absorption cooling system with LTES | The system is installed in a three-storey building with cooling demand of 35kWh·m ⁻² ·y ⁻¹ and heating demand of 63 kWh·m ⁻² ·y ⁻¹ . | Maximum net present value; minimum discount payback period | | The economic analysis of sensible heat storage, latent cold storage and latent heat storage was carried out in this paper. The sensible heat storage has an economic competitive advantage. The cost of latent storage unit is acceptable only if the price of natural gas is high or the cost of pcm is low. | [227] |
| Integration of ejector cooling system and Photovoltaic/ Thermal system with LTES | The thermal output of the Photovoltaic/ Thermal system is 28,816 kW. | Payback period | | The payback period of photovoltaic thermal ejector cooling systems with PCM units is 3.405 years. The payback period is very sensitive to cooling costs. When the cooling cost is below \$26 per ton, the payback period is less than 4 years. | [228] |
| Solar still with LTES | Daily water production capacity of 2-4L/m ² | Total cost (including operating cost, maintenance cost and fixed cost) | PCMs | This paper compared the economic competitiveness of composite materials (mixture of paraffin and black gravel) and phase change materials (paraffin) through cost analysis. The cost of a solar still system with composite material is 0.0014\$ / Lm ² , which is 27% lower than that with paraffin. | [229] |

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|--|--|---|--|--|-------|
| Concentrating solar power applications with LTES | The demand thermal storage power of 3000MWth | Capital cost | | The system cost for different pipe lengths, HTF capacity and PCMs calculated in this paper is between 17.745\$/kWhth and 23.744\$/kWhth. It is proved that the shell-and tube type LHTES is economically competitive compared to the two-tank molten salt indirect thermal storage system. | [230] |
| Solar power plants with LTES | The annual capacity of 100MWe | Levelized Cost of Energy (LCOE); total cost; uncertainty analysis | | This paper compared the economic competitiveness of sensible heat storage, latent heat storage and thermochemical energy storage in solar power system. The cost of the thermal storage system is determined primarily by LCOE. Based on the optimal capacity configuration, the total investment cost of solar power plants with different heat storage technologies is calculated. The uncertainty analysis is used to evaluate the cost controllable range of each system. The LCOE of the phase change thermal storage system is 19 cents/kWh; because of the wide pricing range of commercial PCM, the LCOE of commercial PCM is 6 to 43 cents/kWh; the overall system cost is 507 million. The cost of the latent heat storage system is lower than the cost of thermochemical energy storage, higher than that of the sensible heat storage system. | [231] |
| Concentrating solar power plants with LTES | The annual capacity of 200 MWe | System Cost Limitation(< \$87.95 million); LCOE (< 6 cents/kWh); exergy economy analysis (>95%) | Tank radius, tank height, HTF channel width/length and longitudinal spacing between heat pipes of LTES | In this paper, the geometric parameters of phase change heat storage unit were designed by means of economic analysis. The results show that the cost of the thermal storage unit is a monotonic increasing function of the capsule radius, the tank radius and the channel width/length. It is also a monotonic decreasing function of the longitudinal spacing of the heat pipes. Three evaluation methods can help determine the range of design parameters. | [232] |

Figure captions

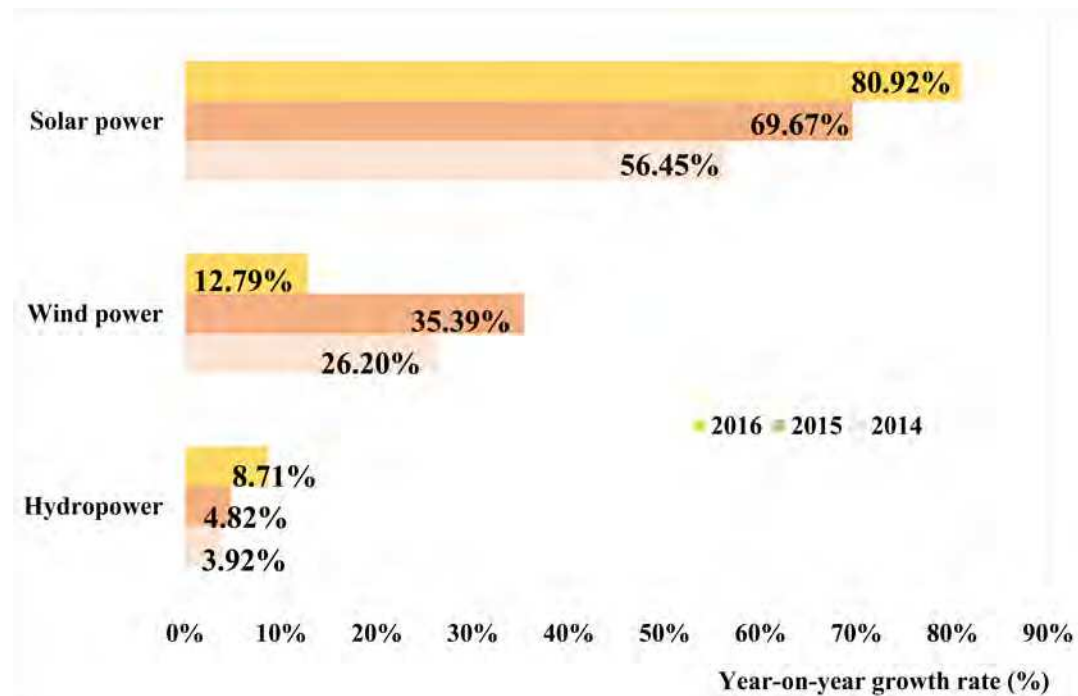
Figure 1. The installed capacity of renewable energy power generation in China

Figure 2. Technical classification of solar air conditioning systems

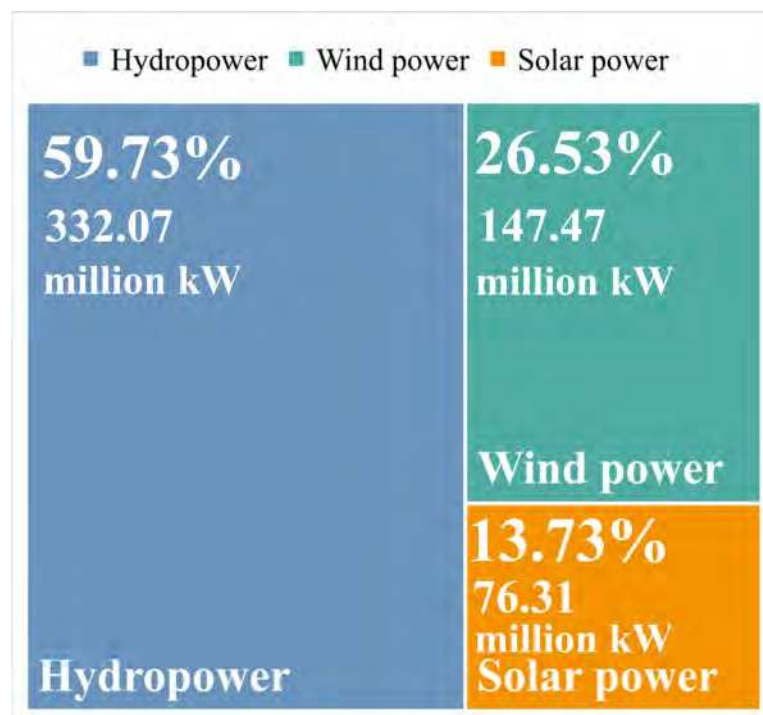
Figure 3. The thermal storage technology and the classification of PCMs

Figure 4. The schematic diagram of solar desiccant air conditioning system

Figure 1



(a) Year-on-year Growth Rate of Renewable Energy Installation Capacity in China from 2014 to 2016



(b) China's Renewable Energy Installation Capacity by the end of 2016

Figure 2

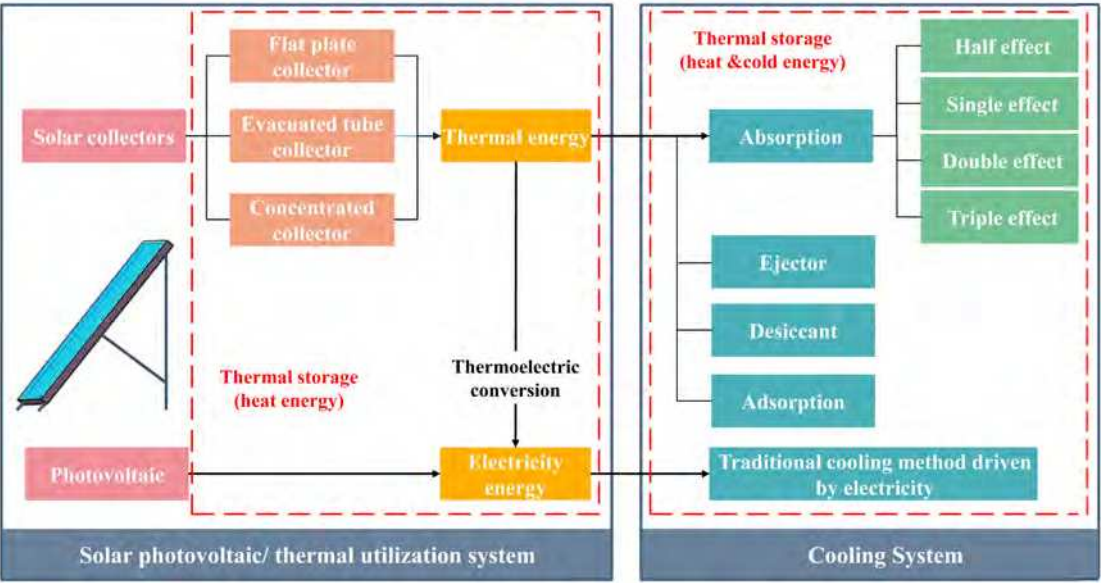


Figure 3

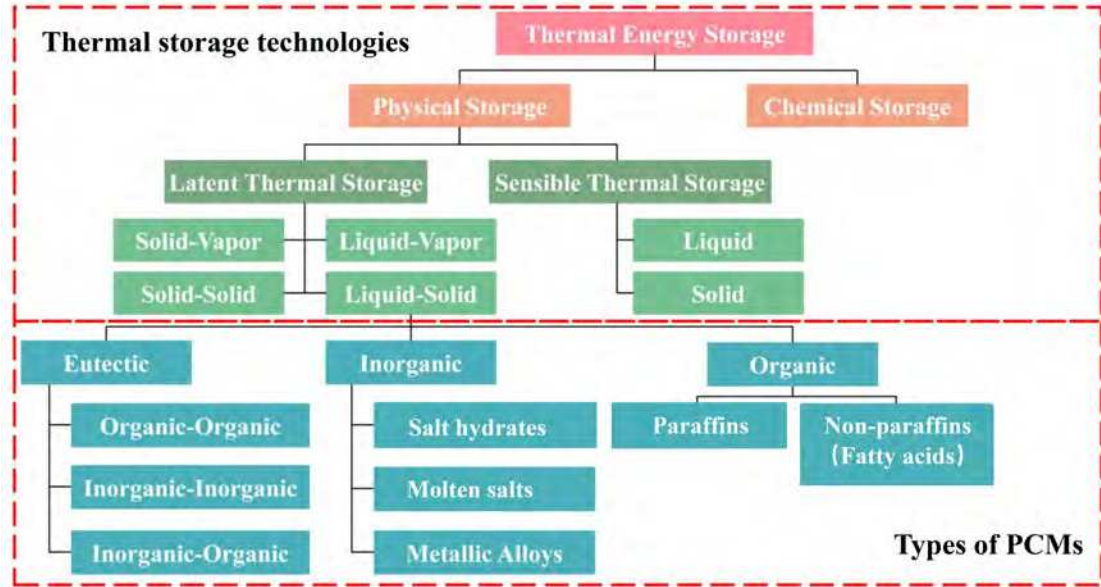


Figure 4

